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THE UNIVERSITY OF ALBERTA

GLACIGENIC STREAMLINED LANDFORMS
NEAR ST. PAUL, ALBERTA

by

© NORMAN JONES

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

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EDMONTON, ALBERTA
SPRING, 1981

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J. Shaw
Supervisor

D.I. Gough

Date April 23 1981

Abstract

The Lac la Biche fluting and drumlin field originates at Lac la Biche, Alberta and extends southeastwards almost to North Battleford, Saskatchewan, a distance of approximately 390 km. The northwest - southeast orientation of the field is transverse to the regional northeast to southwest ice flow direction of the Laurentide ice sheet in Alberta. The Lac la Biche field appears to be a result of a late resurgence of a stream of Wisconsin ice during deglaciation of this region about 11,000 years ago, and aerial photograph evidence shows it to be contemporaneous with an ice stream from the Cold Lake area to the northeast. The two ice streams converged just north of St. Paul, Alberta and flow continued to the southeast. The purpose of this investigation is to determine the genesis of the glacial landforms in the Lac la Biche field.

Field investigations, including till fabric, texture and lithology show evidence of widespread glaciotectonic activity illustrating frozen-bed conditions and compressive ice flow probably ensued at some point during ice advance. The smooth streamlined appearance of drumlins and flutings indicates a transition into wet-based conditions and, possibly, extending flow. A general interpretation holds that initial frozen-bed conditions and compressive flow caused glacial thrusting and plucking of blocks of basal debris near the margin of ice. The blocks lodged at the glacier bed and resisted further movement. With continued advance, thawed-bed conditions were encountered and deposition in a low pressure zone created in the lee

of these obstacles occurred. Lateral transport of debris in the lee of the blocks was accomplished as a result of converging secondary flow cells created by the basal pressure gradient. Some till fabric analyses show a 'herring-bone' fabric pattern supporting the existence of converging secondary flow.

Auger holes drilled through three flutings, numerous road cut examinations and subsequent till textural and lithologic analyses, show only one till is present in the streamlined landforms. This reduces the validity of any hypothesis to explain the landforms which requires the addition of two or more till layers during consecutive ice advances. It is concluded the entire formation of the drumlins and flutings occurred during a single ice advance.

Acknowledgements

I wish to thank Dr. John England for his helpful comments and continued support during the final stages of this thesis, and Dr. Ian Gough for taking the time to read and evaluate this thesis under less than ideal circumstances. Special thanks go to Dr. Mark Fenton of the Alberta Geological Survey who provided funding for the fieldwork and has greatly improved my expertise in field geomorphology over the years.

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Finally, I wish to acknowledge the person who provided not only very valuable and constructive comments throughout the writing of this thesis, but also provided much needed moral and practical support during the final stages when it was really necessary. Dr. John Shaw's continued belief in my work and myself made the completion of this thesis possible. Thanks John.

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Chapter I

Landform Description and Literature Review

Introduction:

The genesis of ice-moulded, streamlined landforms has received a great deal of attention and yet still remains controversial. Many theories, some dating to the late nineteenth century, have been proposed to explain their development (Chamberlain, 1883). It is difficult to determine the genesis of these landforms as they originate at the base of glaciers where direct observation of their formation is practically impossible. The formation of small-scale flutings, less than 2 m high (Boulton, 1976), at the base of contemporary ice sheets has been observed (Dyson, 1952; Hoppe and Schytt, 1953; Baranowski, 1970; Paul and Evans, 1974; Boulton, 1976; Morris and Morland, 1976). However, no such observations have been made for large-scale flutings, which attain heights of up to 25 m (Flint, 1971) and develop at the base of continental glaciers.

In this report large-scale streamlined landforms will be investigated and a number of relevant theories examined critically (Gravenor and Meneley, 1958; Smalley and Unwin, 1968; Shaw and Freschauf, 1973; and Moran et al., in press). A glacial history of the area under study will also be outlined.

Description of Features:

The three principal types of streamlined landform in the study area are drumlins, drumlinoids, and flutings. Drumlins have an ovoid shape and resemble an egg half-buried beneath the surface. The stoss side of a drumlin faces up - glacier, and the widest and highest portion of the drumlin is located near this end. Drumlins are generally 1 to 2 km long, 400-600 m wide and 5-50 m high (Flint, 1971).

Flutings are long, straight, parallel ridges which lack the longitudinal asymmetry of drumlins. A fluting crest generally maintains approximately the same height throughout its length. Flutings have been observed to occur in two distinct size ranges, usually termed small-scale and large-scale. Small-scale flutings are usually less than 2 m high, about 3 m wide, and up to 1 km in length (Boulton, 1976). Large-scale flutings show a much wider range in size. Flint (1971) gives the following representative figures: length, 20 km; width, 100 m; and height, 25 m.

Fields of large numbers of flutings and drumlins are normal, although drumlins may occur as isolated features. Gravenor and Meneley (1958) showed that flutings in fluting fields may possess a regular transverse wavelength, while Smalley and Unwin (1968) discovered drumlins occur in a more random pattern. In addition, Reed, Galvin, and Miller (1962) found a multimodal distribution, with some indiation of periodicity, for drumlin spacing, while Trenhaile (1971) found both random and regular drumlin spacing patterns.

Drumlinoids, as the name implies, are morphologically similar to drumlins, but have poorly developed stoss ends and tend to be irregular in form. Drumlinoids may be, in some instances, a transitional feature between drumlins and flutings, or perhaps partially formed drumlins. Figure 1 shows a comparison of drumlin, fluting, and drumlinoid size and shape.

Drumlins, drumlinoids, and flutings may be composed of a variety of materials including till of varying textures, stratified

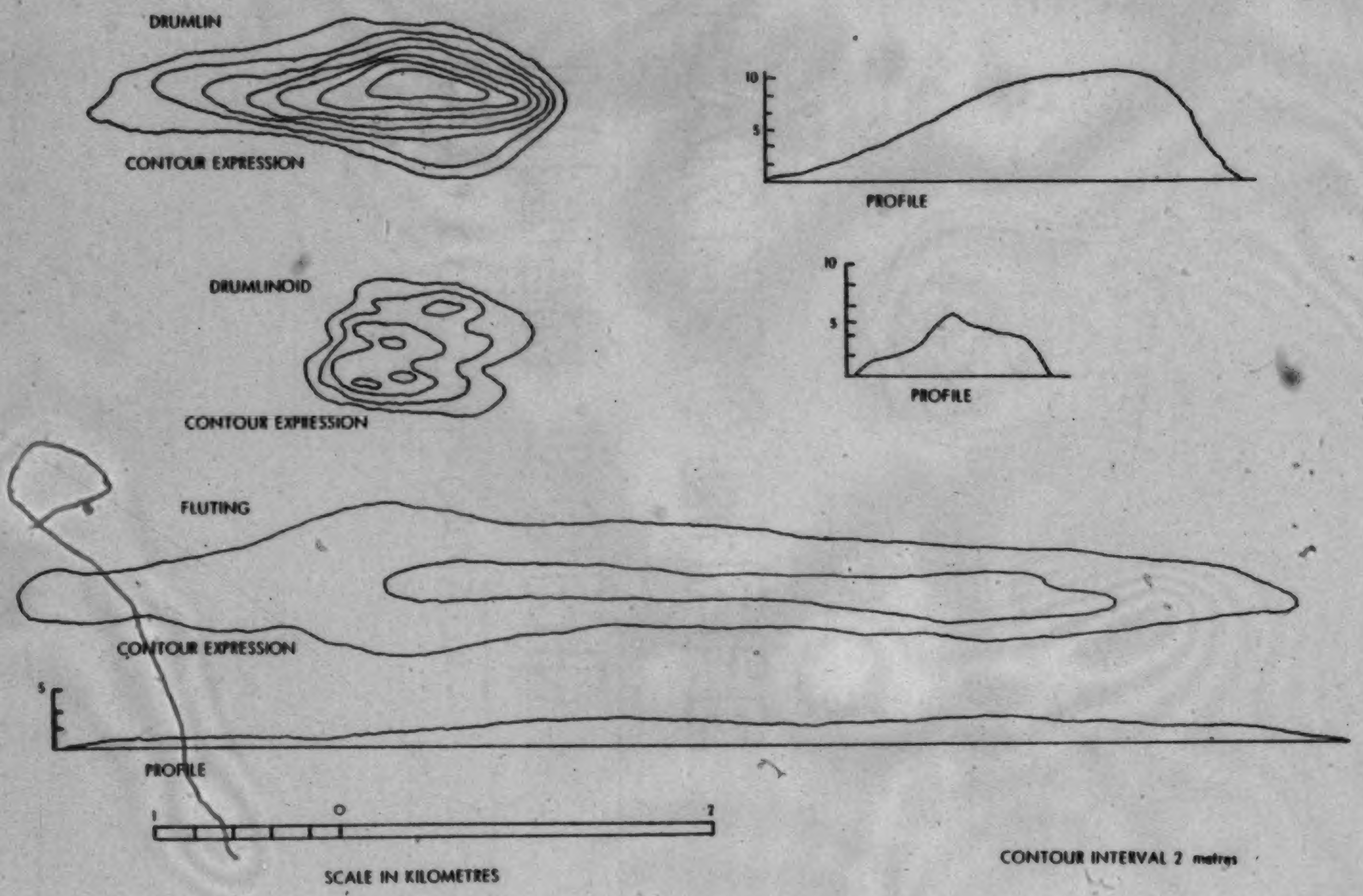
DRUMLIN
CONTOUR EXPRESSION
10
5
PROFILE
DRUMLINOID
CONTOUR EXPRESSION
10
5
PROFILE
FLUTING
CONTOUR EXPRESSION
5
PROFILE
1
0
2
SCALE IN KILOMETRES
CONTOUR INTERVAL 2 metres

Fig. 1 Comparison of Landform Shape (after Freschauf, 1971)

drift, or bedrock. Additionally, a drumlin may have a rock core (Gillberg, 1976). The long axes of drumlins, drumlinoids and flutings are orientated parallel to the direction of regional ice flow. Figure 2, compiled from aerial photographs and mosaics, shows the location of drumlin and fluting fields in Alberta.

Formation of Drumlins:

Early theories on drumlin formation belong to two main groups, erosional, and depositional. Many of the proponents of depositional theories believe that drumlins are formed by deposition of till around a rock or debris obstruction. For example, Chamberlain (1883) suggested that deeply imbedded rock blocks caused accumulation of debris, thus forming drumlins. Slater (1929) considered that drumlins along the shoreline of Lake Ontario were formed from a till core which initiated accumulation. Alden (1918) found that some drumlins in Wisconsin have rock cores, so he suggested that a transverse stress in the glacier may have caused the formation of debris piles which may then have been shaped into drumlins. Armstrong (1949) believed drumlins were built up from cores of frozen till. Other proponents of a depositional mode of formation (Alden, 1918; Goldthwait, 1924; Fairchild, 1929; Flint, 1947) reasoned that, since some drumlins show layering approximately parallel to the landform surface an accretional explanation is probable.

Shaler (1889) and Gravenor (1953) proposed erosional theories which were developed on the presumption of two ice advances or an intermittent advance. Shaler (1889) proposed that drumlins in the New England area were formed by two glaciations, one to deposit the

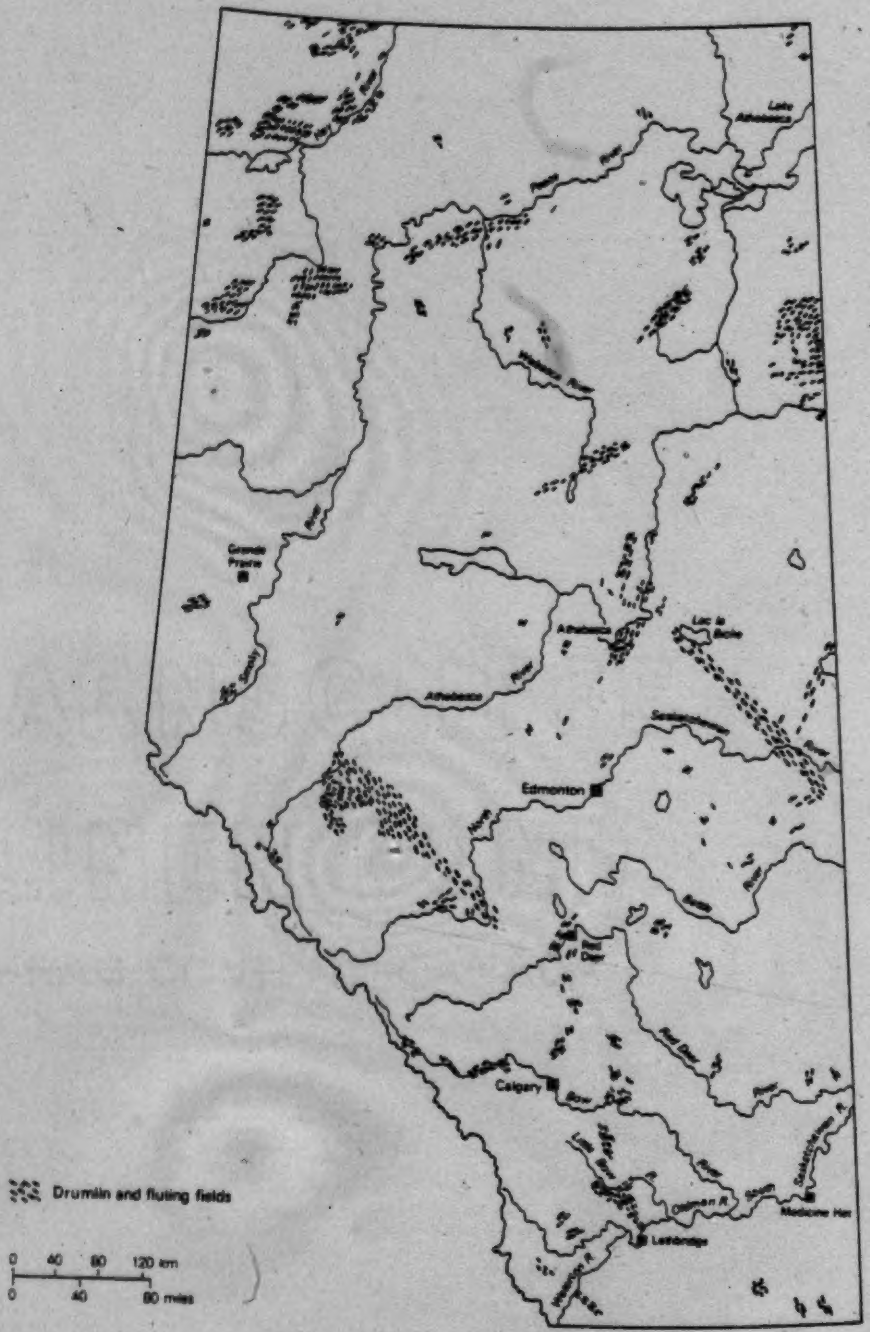
Lake Athabasca
Peace
River
Wabasca River
River
Grande Prairie
Smoky
Athabasca
Lac la Biche
Athabasca
River
Saskatchewan
River
Edmonton
Red Deer
Battle
Red Deer
Calgary
Bow
River
Oldman R.
Medicine Hat
Saskatchewan R.
Lethbridge
Drumlin and fluting fields
0 40 80 120 km
0 40 80 miles

Fig. 2 Location of Drumlin and Fluting Fields in Alberta, Compiled from Alberta Government Aerial Photographs and Mosaics

till and one to erode and mould it. Gravenor's (1953) modified erosional theory depends on two postulates (p. 679):

1. Masses of till and stratified material would be deposited at the front of an advancing glacier if there was a temporary halt during the ice advance.
2. A resurgence of ice would ride over this drift, eroding and shaping it into drumlins.

Tarr (1894) thought that the similarity between rock drumlins and drumlins composed of till suggests that both could be explained by erosion.

In recent years, several authors have considered the combined effects of erosion and deposition in the formation of ice-moulded landforms. Smalley and Unwin (1968) proposed a theory based on the dilatation of the material directly below the glacier bed, and the deformation of this sub-glacial drift by the tangentialstress exerted by the glacier. Theyproposed that the sub-glacial debris is composed of boulders and large rock particles in a clay-water matrix which is continually deformed and sheared by ice movement. A large initial stress is necessary for the initiation of dilatation and deformation of the debris. Under tangential stress the material expands but exerts a high resistance to deformation until maximum dilatation occurs. Deformation continues freely at stresses above that necessary to cause maximum expansion. Drop in stress below a certain level causes deformation to be arrested. Once a portion of the deforming material collapses and becomes static, it can then be shaped by the flow of other debris-rich ice around it. Smalley and Unwin (1968) divided the glacier into three zones of basal stress. The ice-marginal zone has a stress level less than the minimum for subglacial deformation to occur, directly up-glacier is a region where stresses are in the necessary range for drumlin formation to occur; the stress level further up-glacier is sufficiently great to produce general subglacial deformation.

Formation of Flutings:

The genesis of glacial flutings has been considered to be similar to drumlin formation, although it is clear from obvious morphological differences between the two features that the processes of formation must differ somewhat in kind or in duration. However, theories on drumlin formation, such as that of Smalley and Unwin (1968) must be considered when interpreting fluting development.

Small-scale flutings have been studied widely (Dyson, 1952; Hoppe and Schytt, 1953; McPherson and Gardner, 1969; Baranowski, 1970; Paul and Evans, 1974; Boulton, 1976; Morris and Morland, 1976; Lawson, 1976). These authors have concluded that, in general, small-scale flutings develop through the depostion of sub-glacial debris in a basal cavity which forms when a glacier passes over a rigid obstacle. This obstacle may be a boulder, bedrock knob, block of frozen till, or a frost heave. Essentially the flutings are formed when unfrozen, water-soaked debris is squeezed, or flows, into a low pressure zone that develops in the lee of these initiating obstacles. Hoppe and Schytt (1953) and Lawson (1976) suggest frozen debris is necessary for the formation of longer flutes.

McPherson and Gardner (1969), on the other hand, believe that flutings found in front of the Saskatchewan Glacier, Alberta, were formed in splaying crevasses at the snout of the glacier. Such crevasses create an uneven distribution of pressure at the ice base, with low pressure zones beneath the crevasses. Unfrozen till material is squeezed into these low pressure zones, forming small-scale flutings. Lawson (1976) postulates that flutings at the Spencer Glacier, Alaska, are forming by the deposition of debris from basal ice during ablation. The melting terminus of the glacier is composed of an upper zone of clear, white ice and a lower zone of debris-rich ice, which contains layers of alternating high and low concentrations of sediment. The upper surface of the basal debris-rich ice is ridged and the ridges lie parallel to the direction of the main flow of the glacier. This ridged appearance is maintained as fluting forms when meltout of the debris-rich basal ice occurs.

The flutings found in the area under study in this thesis are of the second type: large-scale flutings. The size of these features (approximately 10 m high) causes difficulty in the application of the obstacle hypothesis proposed for the small-scale features. This is not to say that a theory could not be applicable to both types. However, the large size differential between them seems to suggest that different processes are at work in each case.

One of the principal mechanisms that has been postulated to explain large-scale flutings involves linear belts of high and low pressure beneath the ice (Gravenor and Meneley, 1958) and secondary flow cells in ice sheets (Shaw and Freschauf, 1973; Shaw, 1975; Shaw, in press). Gravenor and Meneley (1958) suggest from their investigations that the regularity of the fluting wavelength must be (p.727), "controlled by some physical property of the glacier which gives rise to periodic variations in erosive capacity in a direction transverse to the direction of the flow". They suggest flutings are created by the presence of (p. 727), "alternating parallel high and low pressure zones at the base of the ice." Gravenor and Meneley (1958) state that lineations near the crests of the ridges are parallel to regional ice-flow direction, while those at a depth less than 3.1 m show an orientation oblique to the main axis, indicating the fluting material originated in the grooves alongside the ridges. Also, they observed foliation which dips away from the ridge tops and interpret this to result from material being eroded from a high pressure zone and transported obliquely to the low pressure zone, in a down-glacier direction. Deposition is said to occur from ice which becomes stagnant along these low pressure zones owing to high debris concentrations. The main flow of the glacier then streamlines this material. It is interesting to note that the till which forms the flutings may pre-exist the formative glacial advance. A re-advance of the glacier or two separate ice advances are necessary for a pre-existing till. However, a pre-existing till need not be necessary. If the ice is debris-rich this material may be transported to the low pressure zones by the secondary flow of the ice to form flutings (Shaw and Freschauf, 1973). Only one glacial advance is then required.

In an earlier paper, Gravenor (1953) presented a modified erosional hypothesis which involved the moulding of ice-marginal debris into drumlins. In the paper with Meneley, he provides a process to explain how this happens. Although they offer no theory on how the high and low pressure zones originate they do illustrate how the existence of pressure bands causes fluting development.

Shaw and Freschauf (1973), Shaw (1975), and Shaw (in press) relate the formation of flutings, and in the case of the last mentioned paper, ice-moulded landforms in general, to secondary flow cells in the ice. This theory is similar to Gravenor and Meneley's (1958) differential pressure hypothesis in that material is transported from high pressure zones to low pressure zones where it accumulates and is moulded into a streamlined landform. Separation points of helicoidal flow cells develop at the low pressure zones. Shaw (in press) notes that since adjacent helicoidal cells flow in opposite directions an uncoupling of these cells from the glacier bed may occur at the point of separation, thus allowing glacial meltwater to be present during fluting formation. This may partly account for the presence of stratified material in many flutings.

One other hypothesis of streamlined landform genesis which relates directly to the area under study is that involving glacial thrusting. Moran _et_ _al_. (in press) explain that landforms such as flutings and drumlins may be developed from deposition in the lee of blocks of material that have been plucked from the bed of a cold-based glacier by a thrusting mechanism. This glacial thrusting, or plucking, is expected to occur preferentially where the ice advances upslope under compressive flow, thus increasing the ability of the ice to incorporate basal debris (Rothlisberger, 1968). Thrusting is said to be favoured where ice advances over a buried aquifer, which causes elevated porewater pressures, and thus, a reduction in the shear strength of the subglacial material. It should be pointed out here that although Moran _et_ _al_. use the occurrence of thrusting in the region of aquifers as supporting evidence for the importance of high water pressure and reduced strength, the aquifer might also simply serve to provide water for ice segregation as required by Weertman's (1961) model to be discussed later. Other areas of preferred glacial thrusting are along major ice-marginal positions where the ice was under non-steady-state conditions and compressive flow, and in regions where the dominant surficial deposit is lacustrine clay, an inherently weak sediment (Moran _et al_., 1981). In addition, they list three conditions favourable to thrusting: a frozen bed; pre-existing planes of weakness (such as bedding or jointing); and decreased shear strength in rock or sediment caused by locally elevated porewater pressure.

Weertman (1961) provided a different mechanism for debris block incorporation which involves the refreezing of basal meltwater. He postulated that meltwater, produced at the glacier bed by frictional heat of sliding and geothermal heat, may be transported from a zone where the glacier base is at the melting point to a zone where the 0° isotherm lies below the glacier bed. A block of basal debris lying above the 0° isotherm may then be frozen to the glacier bed. Incorporation of this block then occurs through deformation of an underlying layer of regelation ice.

Once a block of debris has been incorporated into the ice by either of the above mechanisms a low pressure zone may be formed in its lee if the ice is found to move around the block, for instance should the block lodge. Debris-rich ice may then flow laterally from either side of the block and accumulate in the lee zone. The postulated transverse movement in the ice corresponds to the secondary flow which has been inferred from the 'herring-bone' fabric found in streamlined landforms (Evenson, 1971; Shaw and Freschauf, 1973). Moulding by ice flowing around the zones of high debris concentration may then produce a streamlined form.

An outstanding problem is to provide some dynamical explanation for the lateral component of ice flow. This secondary flow may be driven by differential pressures related to the ice characteristics alone. Alternatively, the flow may be a response to pressure gradients produced by interactions between the glacier and its bed. The thrust block hypothesis involves this second type of mechanism.

Moran *et al*. (1981) cite numerous examples of streamlined terrain on the plains of North America which they think may have been formed by this thrusting/streamlining process.

Summary

Drumlins and flutings are probably genetically related. Indeed, flutings may represent continued elongation of initial drumlins (Gilberg, 1976). In both cases, their positive relief characteristics and streamlined appearance, together with systematic internal structure, suggest a formative process of both an erosional and depositional nature. The results of fabric studies (Gravenor and Meneley, 1958; Evenson, 1971; and Shaw and Freschauf, 1973) indicate a transport of material obliquely down-glacier. Subsequent deposition and moulding of this material by ice flow are postulated.

Since glacial flutings and drumlins occur in crystalline bedrock (Smith, 1948), as well as in till and stratified materials, it seems that the type of material present is not a major controlling factor in formation. Thus, it is suggested that the flow characteristics of the ice during formation are of greater importance.

Flint (1971, p. 106) suggests that only two general conclusions can be made about a region where streamlined landforms exist:

1. The presence of such forms establishes the existence of an actively flowing glacier at the time of formation.
2. The long axes of streamlined forms are a more reliable indicator of the general direction of movement of a former glacier than are striations, because they are less influenced by local topography.

Chapter II

Study Area

Introduction

The study area, located in east-central Alberta near the towns of St. Paul and Elk Point, lies within a fluted region extending from Lac la Biche, Alberta, southeastwards to North Battleford, Saskatchewan, a distance of approximately 390 km. The area of study, which is illustrated in Figure 3, has a length of approximately 80 km and a width ranging from 15 to 25 km. Northwest of St. Paul, the streamlined terrain is characterized by relatively short (≤5 km) and high (≈5 m) flutings, with ubiquitous drumlins and drumlinoids (Figs. 4 and 5). The flutings become more elongated (15-20 km) and lower (≤1 m) down the former ice flow direction, nearer Elk Point (Fig. 6), while drumlins and drumlinoids in this region are found only on the southwest edge of the fluting field. The distribution of the surficial glacial deposits of the area is shown in Figure 7.

The study area was chosen because the large number of road cuts provide numerous exposures of the interior of the landforms, and the proximity to the towns of Elk Point and St. Paul provided relatively easy access to accomodation and supplies.

Bedrock Geology

The local bedrock is of Upper Cretaceous continental and marine shales and sandstones which dip gently to the south and southwest (Ellwood, 1960). Clay ironstone layers and nodules occur at numerous locations throughout the study area, and are included in a large thrust

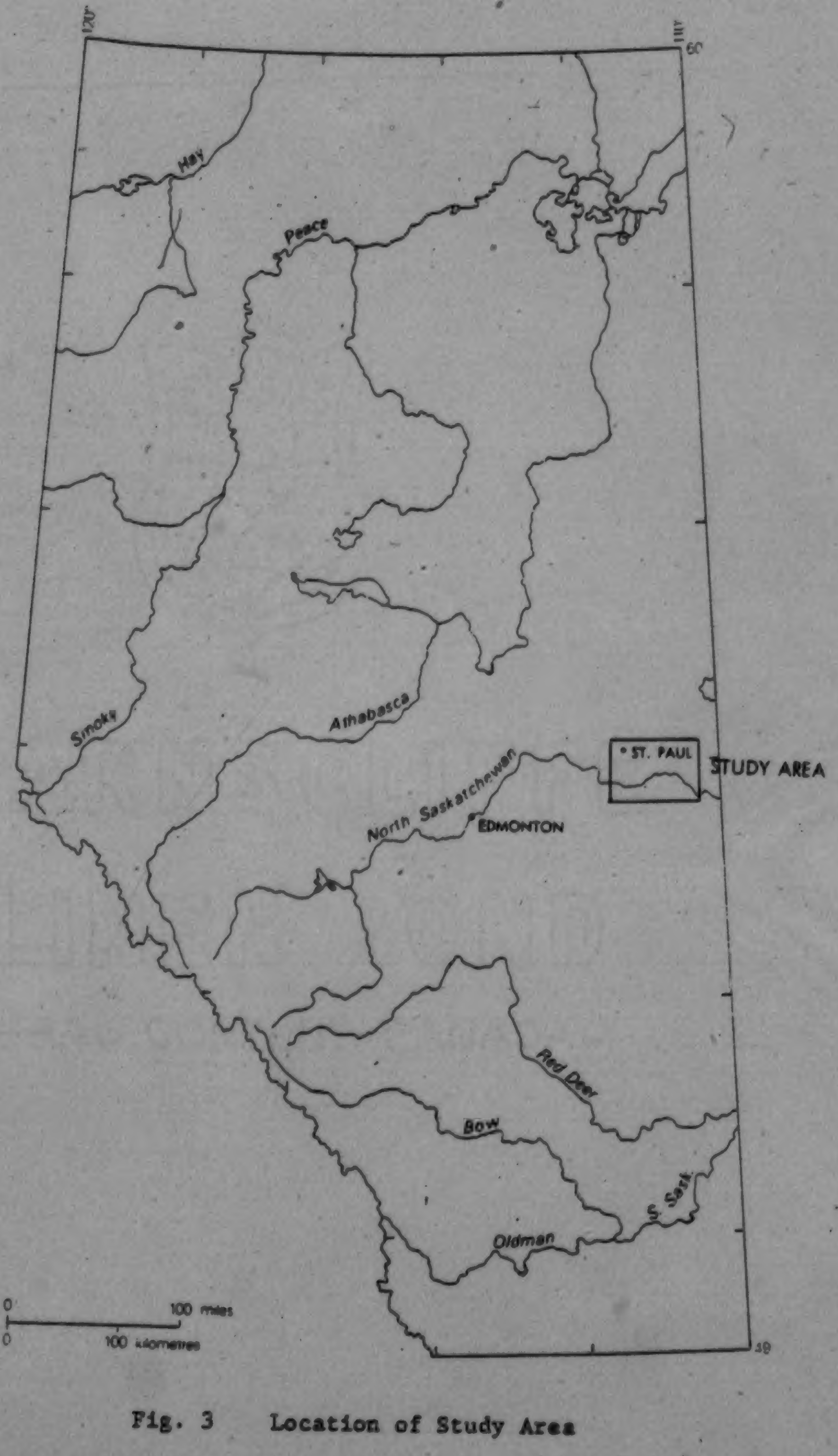
120°
110°
60
Hay
Peace
Smoky
Athabasca
North Saskatchewan
EDMONTON
ST. PAUL
STUDY AREA
Red Deer
Bow
Oldman
S. Sask.
0
100 miles
0
100 kilometres
49

Fig. 3 Location of Study Area

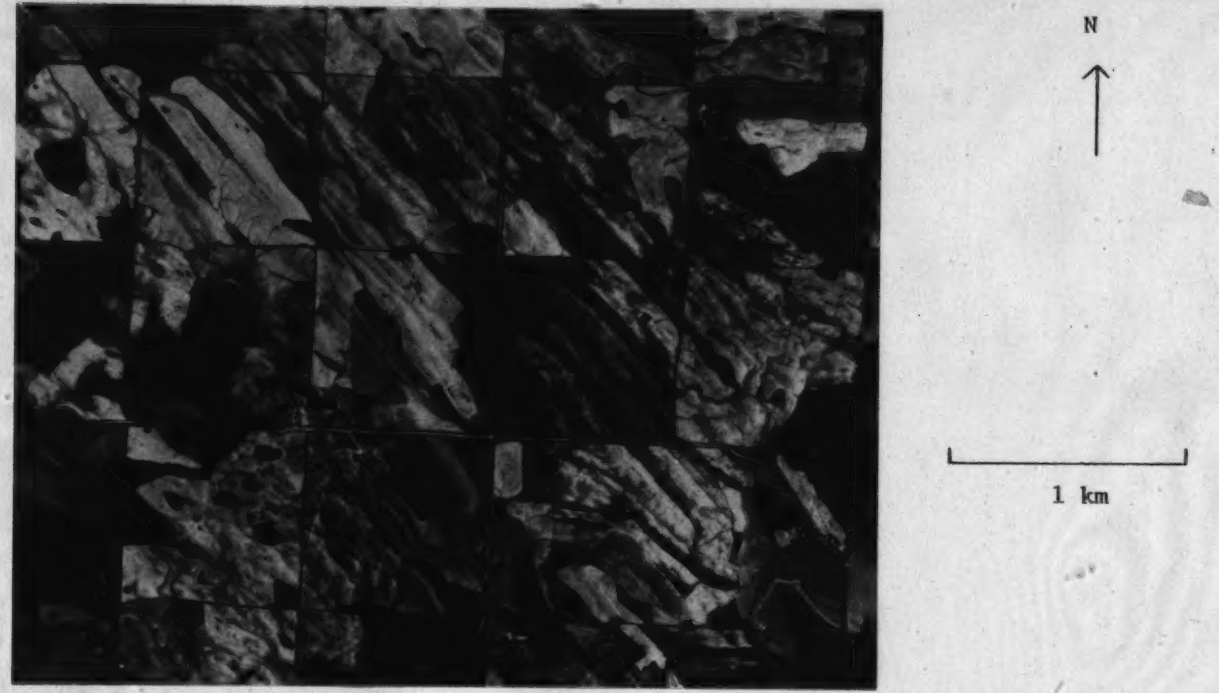

Fig. 4 Short High Flutings
(Alberta Government Photo #R6530.26.865 R69.5321.21
Location: Center, Township 57, Range 8, West of the
4th Meridian, N.T.S. Map Sheet 73E/14)

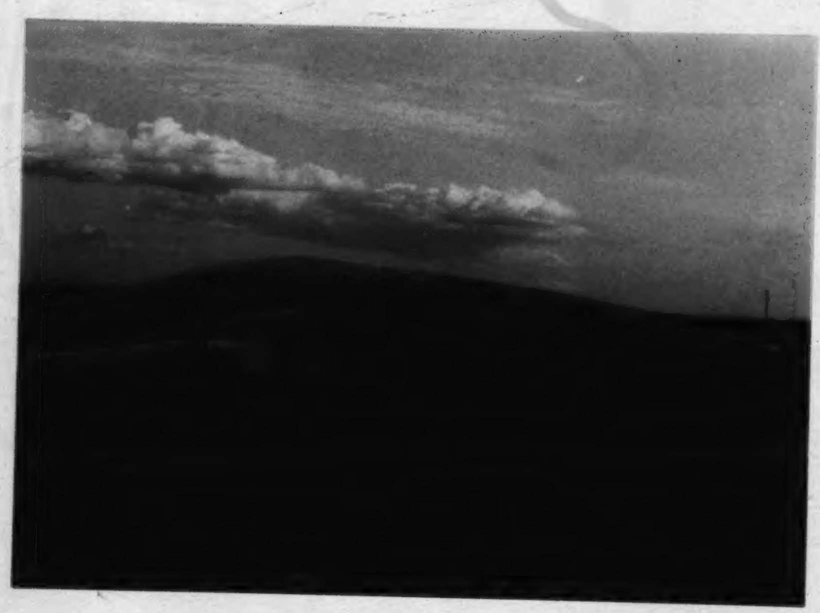

Fig. 5 Drumlin
(Location: Township 58, Range 9, Section 14, L.S.D. 2,
West of the 4th Meridian, N.T.S. Map Sheet 73L/3)

Fig. 6 Long Low Flutings
(Alberta Government Photo #R6530.26.965 R80.5322.26
Location: N.E., Township 57, Range 7, West of the
4th Meridian, N.T.S. Map Sheet 73E/15)

block on the southwestern edge of the fluting field (Fig. 8). Within this thrust block 2 m of brownish-grey shale overlies a thin (0.2 m) layer of ironstone, which in turn overlies a dull yellowish brown sandstone 3.5 m thick. The exposed thickness of the thrust block is approximately 8 m. Bedrock exposures are common in the southeastern part of the study area and are also found along the banks of the North Saskatchewan River.

The surface expression of the bedrock of the area has been greatly influenced by the glaciotectonics, as evidenced by the numerous cases of thrusting and exposures of severely contorted bedrock.

Glacial History

The detailed surface topography of the study area reflects mainly the Wisconsin glaciation. This glaciation, which began about 80,000 to 100,000 years ago (Frye et al., 1968) remodelled the previous landscape by covering or removing most of the earlier Quaternary deposits. The streamlined landforms discussed in this report are, then, products of Wisconsin glaciers. Specifically, they are probably products of the late stages of the last Wisconsin ice advance, as it is improbable that these landforms were maintained throughout the Wisconsin during which ice sheets extended to the Alberta/U.S.A. border (Prest, 1970). Their formation may reflect a late resurgence of the ice into this area of east-central Alberta, which represented the final advance of ice into this region. It is estimated that the ice retreated from the Lofty Lake area, just northwest of the study area, approximately 11,400 years ago (Lichti-Federovich, 1970), and a similar date is probably applicable to the deglaciation of the St. Paul area.

An intriguing aspect of the fluting field under investigation is its southeasterly trend from Lac la Biche to North Battleford, Saskatchewan. This trend is transverse to the general direction of Laurentide ice movement in Alberta, which was from northeast to southwest (Gravenor and Meneley, 1958). This factor further supports the suggestion that the fluting field was formed by a late stage of the last Wisconsin advance, since surface evidence of an earlier southeasterly ice movement is expected to have been destroyed or greatly modified by the main body of ice.

Air photo and photo mosaic evidence of interaction between the formative ice streams suggests that the flutings of the study area were of contemporaneous formation with a field which extends southwestwards from the vicinity of Wolf, Marie, Primrose, and Cold Lakes (Fig. 9). These two fields will be referred to as the Lac la Biche field, and the Cold Lake field. North and northeast of St. Paul, regional photo mosaics show the ice which produced the Cold Lake field changed from a southwesterly flow direction to a more southerly one as it encountered the Lac la Biche ice. The curvilinear form of the Cold Lake field in plan view may have been produced by the Cold Lake ice converging with a contemporaneous but larger Lac la Biche ice stream which deflected the Cold Lake ice from a southwesterly to a southeasterly course. If this were the case, an enlarged Lac la Biche ice tongue would have resulted. Figure 9 displays the proposed area of convergence.

Stagnant ice topography, illustrated by a hummocky terrain (Fig. 10), is found southwest of the Lac la Biche field. Warren (1937) termed this the Buffalo Lake moraine, while Bretz (1943) called it part of the Viking moraine. Ice stagnation deposits also occur to the northeast of the Lac la Biche field, and southeast of the Cold Lake fluting field. Ellwood (1960) termed this area part of the Coteau moraine. The stagnation which led to the hummocky moraines in both of these areas probably occurred during the northeasterly retreat of the Wisconsin ice.

I suggest that the two large bodies of stagnant ice existed at the two localities mentioned (Figs. 7 and 9) when the late resurgence of the Wisconsin ice occurred. Movement to the southwest was blocked by the large stagnant ice mass in the area southwest of Lac la Biche, which forced the ice to flow to the southeast where it converged with the flow from the Cold Lake region. The combined ice masses advanced along the margin of the stagnant ice located to the east and northeast. Ellwood (1960) terms this re-advance an "ice-walled valley glacier" type because of constriction by stagnant ice blocks on either side. He notes that this remobilization of ice may have been caused by local high snow accumulation rates in the Athabasca area to the northwest. This local accumulation would not affect flow in the large, stagnant ice blocks. No other physiographic controls than the stagnant ice blocks exist to channel the late Wisconsin ice. No significant bedrock highs are present. However, changing thermal conditions at the bed may also have been responsible for local ice streams.

I propose that the readvance of late Wisconsin ice, which was channeled to the southeast by two large stagnating ice blocks, resembled the rapidly advancing, narrow tongue of ice described by Doornkamp and King (1971) for the Tyne Gap area of northwest England.

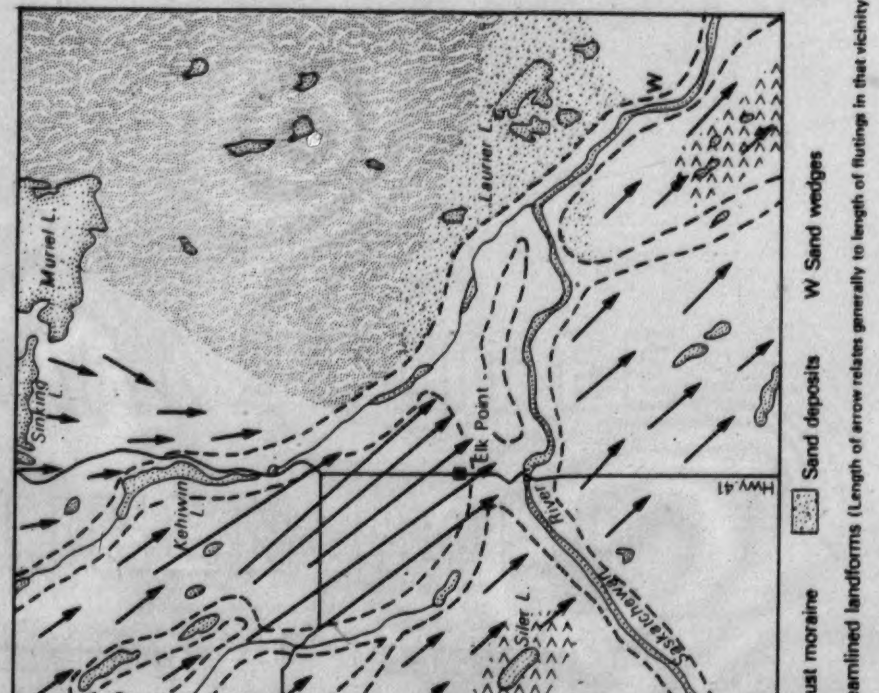
Muriel L.
Sinking L.
Kehiwin L.
Laurier L.
Vincent L.
Elk Point
St. Paul
Hwy. 28
Hwy. 41
Upper Therien L.
Lower Therien L.
Siler L.
L. Eliza
Lac Bellevue
North Saskatchewan River
W
0
10 Km
Stagnation moraine
Thrust moraine
Sand deposits
W Sand wedges
Meltwater channel
Streamlined landforms (Length of arrow relates generally to length of flutings in that vicinity)

Fig. 7 Surficial Glacial Deposits and Selected Landforms

Shale
Clay Ironstone
Sandstone
Till

Fig. 8 Glacial Thrust Block
(Location: L.S.D. 4, Section 36, Township 58, Range 8,
West of the 4th Meridian, N.T.S. Map Sheet 73E/14)

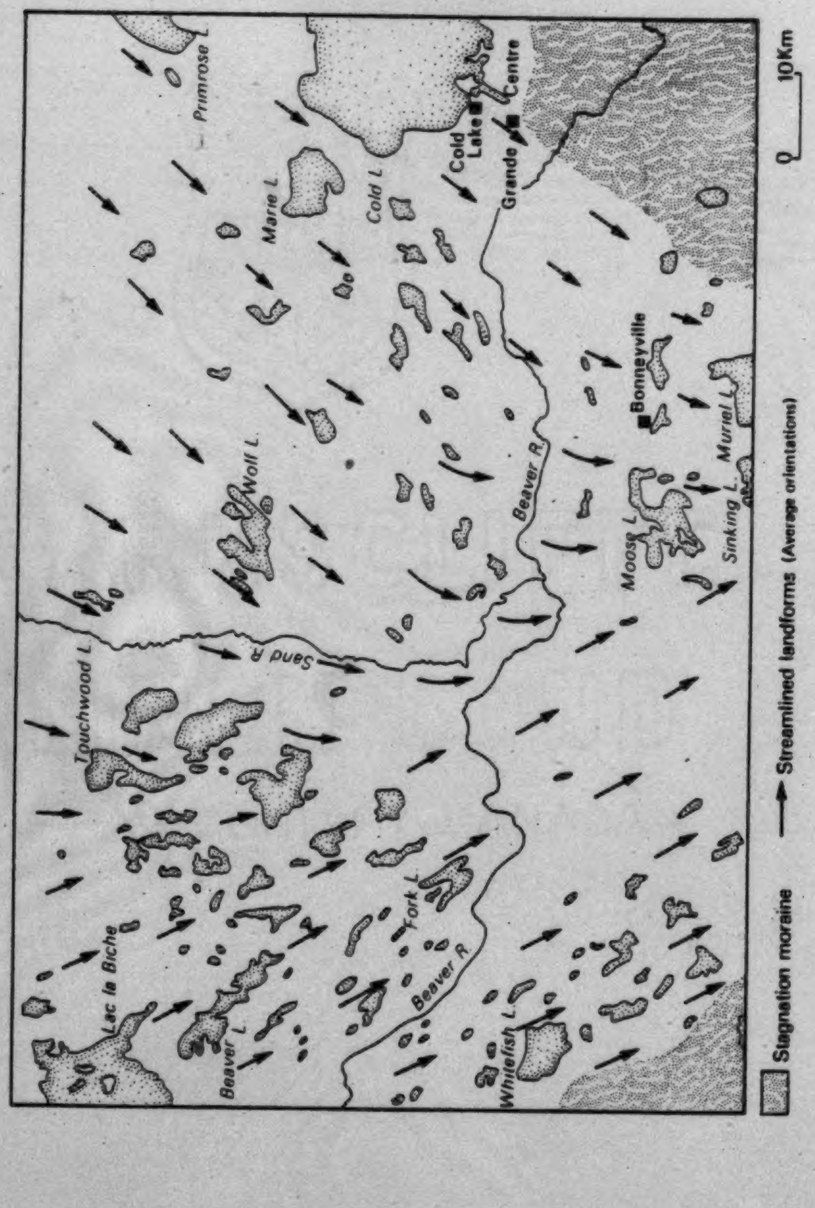
Lac la Biche
Touchwood L.
Primrose L.
Beaver L.
Wolf L.
Marie L.
Cold L.
Cold Lake
Grande Centre
Fork L.
Beaver R.
Sand R.
Whitefish L.
Moose L.
Bonnyville
Sinking L.
Muriel L.
0
10Km
Stagnation moraine
Streamlined landforms (Average orientations)

Fig. 9 Convergence Zone of Cold Lake and Lac la Biche Advances shown by Average Orientations of Streamlined Landforms

Fig. 10 Stagnation Moraine
(Alberta Government Photo #R6530.26.965 R80.5323.43
Location: Center, Township 58, Range 2, West of the
4th Meridian, N.T.S. Map Sheet 73L/1)

From a study of drumlins in the Wigton area of northwest England they postulate that a greater elongation of drumlins indicates rapid glacier flow of constant flow direction. Their reasoning is as follows (p. 302), "... if the flow is constant then the stoss end of the drumlin will protect a long stretch in its lee in which material can accumulate or remain uneroded...". They note if variable flow occurs then the area of lee deposition will be dramatically reduced and may be almost circular. Vernon (1966) in a study of drumlins in Country Down, Ireland arrived at similar conclusions. He noted that the most elongated drumlins were situated in areas of presumed strong, unidirectional flow, while the least elongated drumlins occur where the southward moving Scottish ice was shown to be directed by more powerful Irish ice flowing from the northwest.

The similar genetic and compositional characteristics of drumlins and flutings allow Doornkamp and King's (1971) and Vernon's (1966) ideas to be applied to both types of landform. Thus, using their reasoning, a relatively constant, high rate of flow in the resurging late Wisconsin ice down-ice of the proposed zone of convergence is indicated by the long, low appearance of the flutings near Elk Point (length ≈ 16 km, height ≈ 1 m), and the narrowness of the Lac la Biche fluting field at this point (≈ 10 km). Conversely, at the convergence zone a slower flow is indicated by the relatively short, high flutings (length < 1 km, height ≈ 5 m; Fig. 7).

The absence of ice stagnation features in stratified materials and significant meltwater erosion in the fluted terrain indicate that meltwaters were probably restricted to two large channels (Fig. 7). It is suggested that most of the meltwater drainage flowed directly into

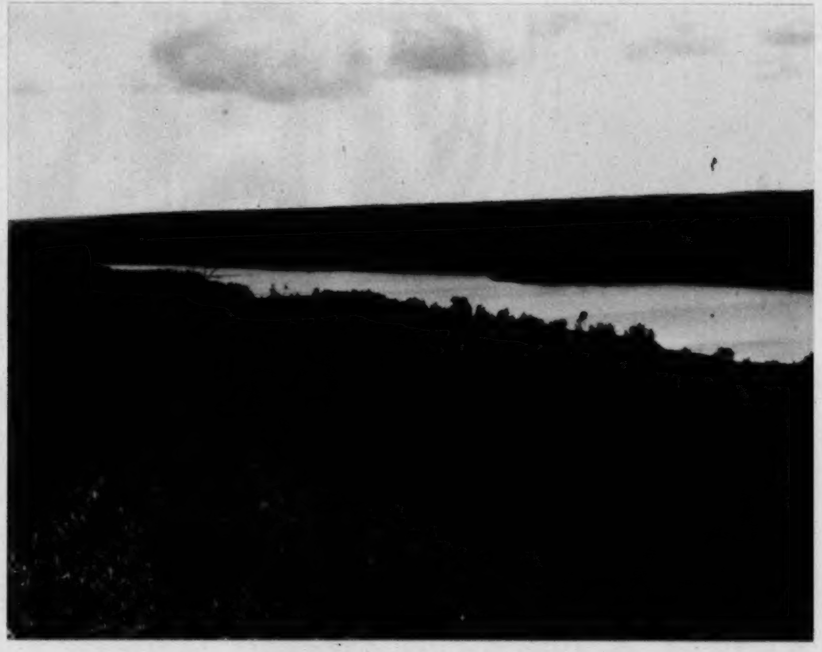

Fig. 11 Meltwater Channel
(Location: Section 15, Township 57, Range 6, West of
the 4th Meridian, N.T.S. Map Sheet 73E/15)

these lateral channels by way of superglacial channels. The Moosehills Channel (Ellwood, 1960; Fig. 11) is one such large channel which follows the edge of the Coteau Moraine, and in many places provides a clear boundary between the fluted region and the ice stagnation topography to the northeast. This meltwater channel forms a natural boundary between the two landform types (Fig. 12). The discharge of meltwaters from the Lac la Biche ice stream may have been in part carried by the system of meltwater channels already formed during the dissipation of the Late Wisconsin ice.

Another factor which must be considered as an influence on the style of deglaciation is climate. The existence of sand wedges and widespread deposits of aeolian sand (Fig. 7) illustrate deglaciation under cold, arid conditions. Meltwater is of reduced importance as a geomorphological agent under these conditions (Shaw, 1977).

No transverse moraines, such as washboard or Rogen moraines, were found within the study area. However, Ellwood (1960) described 'crevasse filling' northwest of Lloydminster which are orientated both transverse and parallel to an ice flow from 325°. In some instances the moraines intersect at right angles with the parallel moraines overlying the transverse ones. In this region the ice advanced upslope from the preglacial valley of the North Saskatchewan River to Lloydminster. According to Clayton and Moran (1974) transverse moraines may be expected where compressive flow occurs, either where ice flows against the landsurface slope, or in the marginal zone of a glacier. They found moraines similar in appearance to the transverse moraines northwest of Lloydminsiter, in Sheridan County, North Dakota. The features in both areas are arcuate in plan, usually concave up-glacier

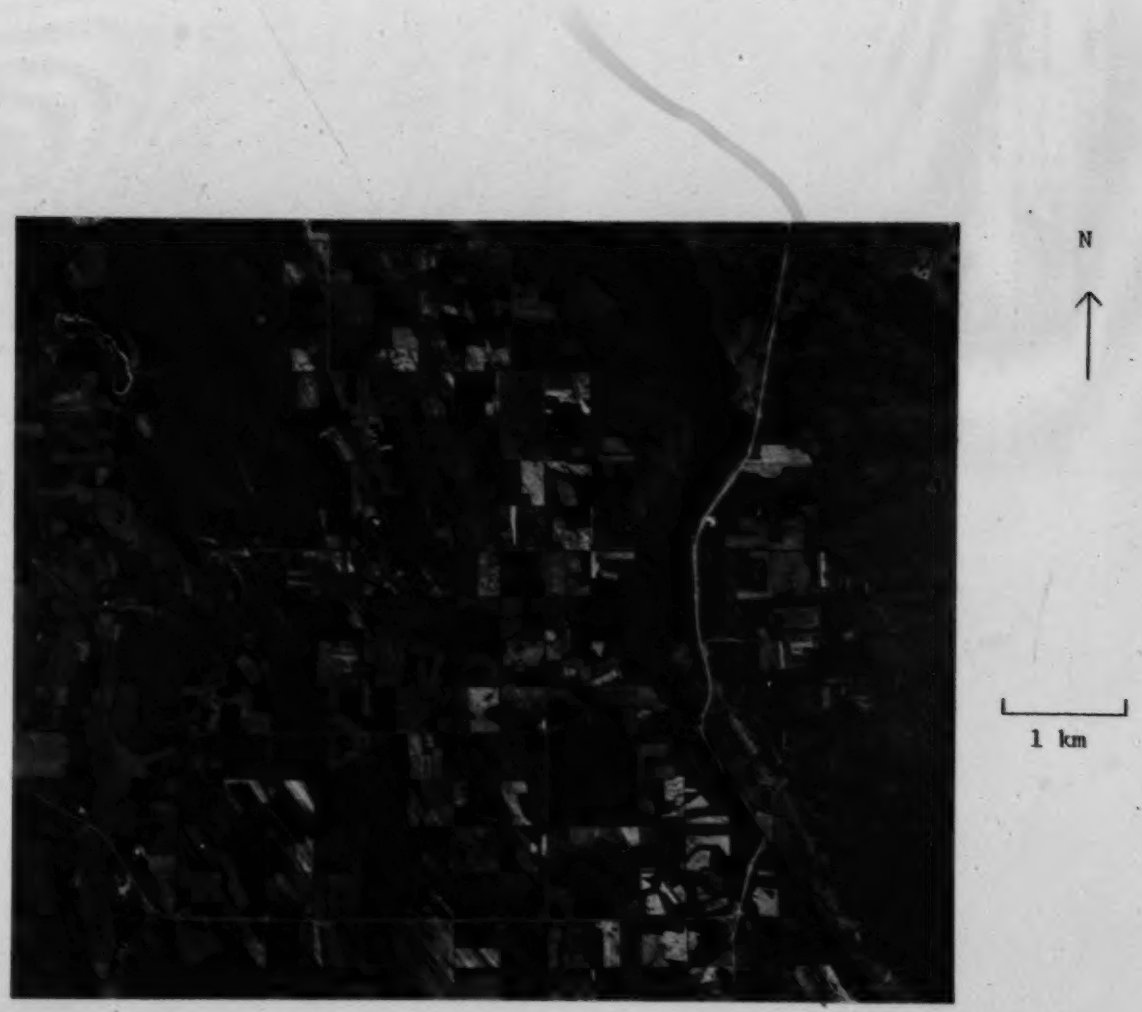

Fig. 12 Boundary between Fluting Field and Stagnation Moraine (dashed line)
(Federal Government Photo #AS1111, Line 39, No. 37
Location: Townships 58 and 59, Ranges 6 and 7, West of
the 4th Meridian, N.T.S. Map Sheet 73L/2)

and contain contorted bedrock blocks, till, and stratified sediments. Clayton and Moran (1974) considered the moraines in North Dakota to be 'transverse compressional features' caused by folding and thrusting of subglacial sediment during compressive flow. The moraines northwest of Lloydminster which are normal to the former regional ice flow direction may have been formed by this 'push' mechanism. Since the ice advanced upslope in this region the flow of ice must have been compressive, and interpretation of local glacial landform genesis must be related to this compressive flow. Also, Röthlisberger (1968) has shown that glacial incorporation is facilitated by compressive flows. I postulate that a majority of the transverse moraines present in the Lloydminster region are 'transverse compressional moraines' similar to those described by Clayton and Moran (1974).

The moraines which parallel the regional ice flow direction and which often overly the transverse moraines were probably deposited during deglaciation, and are true crevasse fillings. Supraglacial and englacial debris which was released during ablation collected in longitudinal crevasses and is preserved as crevasse fillings (Okko, 1955; Gravenor and Kupsch, 1959). Once the ice passed the slope crest near Lloydminster extensional flow was reestablished and flutings became once more pronounced and regular.

Post-Glacial History

Erosion by glacial meltwater as evidenced by meltwater channels within the study area was an active, if somewhat restricted, glacial and post-glacial process. Since the usual northeasterly drainage direction was blocked by the receding late Wisconsin ice all channels extended southeast, usually along the ice front or the margins of stagnant ice borders. There are two large channels within the study area. One, the Moosehills Channel, formed beside the stagnant ice block which deposited part of the Coteau Moraine. The other, the Atimoswe Channel (Ellwood, 1960), is found on the southwest side of the fluted terrain berween St. Paul and Elk Point, and joins the North Saskatchewan River valley just south of Elk Point (Figure 7). This latter meltwater channel now contains Crookedheel Creek and Hook Lake. As this channel is so large, it may represent a standstill position of the main late Wisconsin ice.

The course of the North Saskatchewan River was established as the ice receded to the north and northeast, and the level of this stream represented the base level control for the Moosehills and Atimoswe meltwater channels, as well as for various smaller channels in the area. The North Saskatchewan River has downcut approximately 50 m since deglaciation, and two terrace levels are found at numerous locations along the river. Three sections with terraces are found in Tp 57 R 12, Tp 56 R 6, and Tp 55 R 12. The terraces are approximately 8 m and 15 m above the present river level.

A large expanse of aeolian sand is found to the east of the Lac la Biche fluting field, and on each side of the North Saskatchewan River. These deposits consist of a very fine, dull, yellowish brown sand, and are 0.5 m to 5 m thick. Very few pebbles were found, and faint horizontal bedding is evident in some sections. The source of this sand was probably fluvial and lacustrine sediments deposited during deglaciation.

Underlying the aeolian sand is a coarser, horizontally bedded sand. The coarse texture of the sand and the well-bedded appearance suggest this is an outwash sand deposited by meltwater of the late Wisconsin ice. In some places, south of the North Saskatchewan River the sand is faulted.

A periglacial period of at least several hundred years after the retreat of the main late Wisconsin ice is indicated by sand wedges measuring approximately 1 m at the surface (Fig. 13) These features may be differentiated from ice-wedge pseudomorphs by the well sorted appearance of the enclosed sand, which is easily differentiated from the surrounding till deposits. Also, the sand exhibits vertical layering (Figure 14) typical of sand wedges (French, 1976), and there exists a clear boundary between the sand in the sand wedges and the adjacent till. This is in contrast to ice-wedge casts which usually exhibit an intermixing of the infilling material and the surrounding sediments as a result of the presence of water during thawing of the permafrost and the ice in the wedge (French, 1976). The sand wedges contain the dull yellowish-brown fine sand interpreted earlier to be of aeolian origin.

Sand wedges of this size indicate that periglacial conditions probably existed long after the retreat of the main late Wisconsin ice, and were maintained during the resurgence which produced the flutings under discussion. Thrusting may have been a consequence of the permafrozen conditions at the time of this resurgence.

Fig. 13 Sand Wedges Developed in Till
(Location: L.S.D. 13, Section 27, Township 55, Range 4,
West of the 4th Meridian, N.T.S. Map Sheet 73E/15)

Fig. 14 Vertical Layering in a Sand Wedge Shown in Figure 13
(The lens cap diameter is 53 mm)

Chapter III

Methods and Observations

Introduction

Field and laboratory investigations were undertaken to examine specific elements of the theories outlined in Chapter I. Till fabric, lithology, and texture were studied in an attempt to describe the geomorphological processes which ensued during streamlined landform formation. In addition, field and aerial photographic investigations were undertaken to examine regional glacial landform relationships.

Maps and Aerial Photographs

National Topographic Series maps at scales of 1:50,000 and 1:250,000, and 1:63,360 and 1:80,000 scale aerial photographs were used in the selection and study of the field area.

The aerial photographs were used to examine the interrelationships of glacial landforms in the area, and detailed characteristics of selected landforms and landform suites. The small-scale photos (1:80,000) are extremely useful in the study of landform interrelationships. Identification of landform assemblages and relationships is relatively easy on small-scale photos, and, since only a small number of photos is needed for each region, locating field stations is simple and the need for constant reference to the topographic maps is obviated. The larger-scale photos (1:63,360) were used to study the detailed characteristics of individual landforms and to select sampling and fabric sites. Aerial photographs at both scales and personal photographs taken during a low-level reconnaisance flight over the study area provided much of the information for the map of glacial deposits (Fig. 7). Additional information was obtained through ground reconnaisance and from existing maps of the area (Ellwood, 1960).

Till Deposition and Fabric

Boulton (1975) defined two basic sub-types of till: lodgement till as (p.69)... "Till deposited directly beneath a glacier from moving glacier ice as a result of drag of glacially transported debris against the bed"; and melt-out till as (p.69) ..."Till deposited by slow melting out of debris-rich stagnant ice...". In streamlined landform development these processes may occur simultaneously. The melt-out of stagnant ice beneath active ice may occur simultaneously with fluting or drumlin streamlining.

Holmes (1941) concluded that the long axes of pebbles in lodgement till consistently parallel the direction of ice movement. Other authors (Harrison, 1957; Glen, Donner and West, 1957; Harris, 1969; Boulton, 1970a, 1970b, 1971; and Evenson, 1971) obtained similar results for lodgement or subglacial melt-out tills. Holmes (1941) found that till fabrics are commonly bimodal, showing a primary orientation parallel to ice flow and a secondary one transverse to flow. He suggests that the parallel fabric is due to pebble sliding, and the transverse fabric to rotation about the longest axis. Boulton (1970a, 1971) also observed bimodality and showed that the flow regime of the ice greatly influences the resultant till fabric. Boulton (1970a, p. 219) observed that in Svalbard glaciers, "long axes tend to align themselves in the direction of greatest rate of extension of the triaxial strain ellipsoid, which is parallel to flow in the tensional zone and transverse to flow in the outer zone of compression". However, other authors have found evidence which contradicts this statement. They note parallel orientations in tills thought to have been deposited in zones of compressive flow (Harrison, 1957; Lawson, 1976). Evenson (1971) termed the transverse mode a 'cross-fabric' and postulated that it may be caused by frequent stone collisions, which are directly dependent on the stone concentration. Similarly, Boulton (1970b) noted that the strength of preferred orientation may be weakened during deposition by melt-out by the interaction of stones once separated by ice, an effect which is also directly dependent on stone concentration. Nonetheless, till deposition usually occurs without serious loss of alignment (Harrison, 1957) and till fabrics may be valuable in the study of former ice movements.

Harrison (1957) found that pebbles orientated parallel to ice movement often possess a consistent up-ice plunge. He suggested this results from pebbles being transported along shear planes in the ice which curve upward in the ablation zone of a glacier. Harrison (1957) assumed that up-glacier plunge is preserved even though some rotation to lower plunge angles must occur during depostion by melt-out. Although Harrison (1957) may be right in principle it is not necessary to invoke shear planes, as flowlines in the ablation zone have an upward component independent of the existence of shear planes.

The development of a preferred orientation of till clasts need not occur only in the ice itself. Re-orientation stones in unfrozen till may occur at depths of up to 10 m in response to the shear action of overriding ice (MacClintock and Dreimanis, 1964).

Till fabrics were measured in six streamlined landforms in the St. Paul area. Five of these were taken at sections transverse to the landform main axis, and one at a section parallel to this axis. Sections were chosen to give broad coverage of the study area. Sections 1, 3, 5, and 6 are in flutings, section 2 is in a drumlin, and section 4 is in a drumlinoid (see Fig. 15 for section locations). The longitudinal section occurs at fluting section 6.

Six sample sites were chosen at each transverse section, two at the center (one about 1 m below the ridge crest and one at the base of the section), and two to each side. Following the sample design of Freschauf (1971), a ratio of one-third and two-thirds of the distance from the crest to the trough was chosen for the side sample sites. This scheme allows comparison of the fabric of landforms of various sizes. At site 6, the longitudinal section, two fabrics were taken, one near the top and one near the bottom of the section.

At each fabric site, the orientation and plunge of the long axes of 50 pebbles, sampled from a volume of about $0.5m^3$, were measured using a Brunton pocket transit. Each orientation measurement has a precision of ≅ 2°. The dip measurements have an estimated precision of 1°. The till matrix was carefully scraped away with a knife until a pebble was located. Only pebbles with a minimum 2:1 a:b axial ratio were used, any others were removed and discarded. Each pebble was carefully excavated and the azimuth and dip of the long axis measured in situ. The pebble was then removed to avoid the risk of double measurement. No size or shape limitations were put on the pebbles.

Ostry and Deane (1963), Sitler (1968), Evenson (1971), and

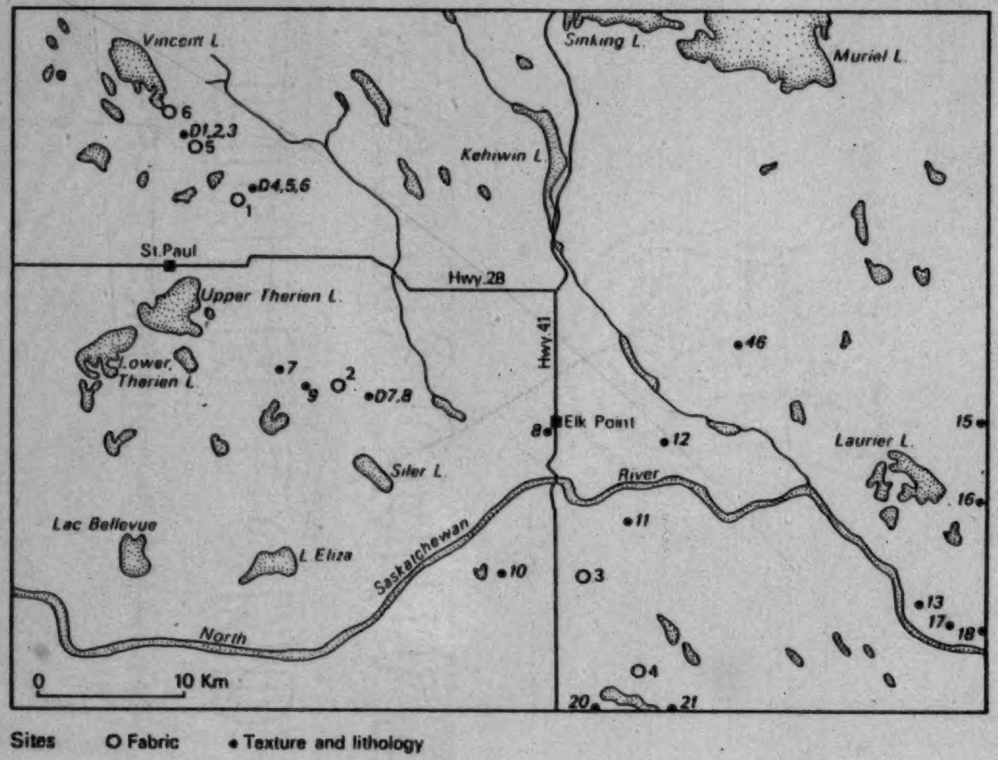
Vincent L.
Sinking L.
Muriel L.
Kehiwin L.
St.Paul
Hwy.28
Hwy.41
Upper Therien L.
Lower Therien L.
Elk Point
Siler L.
Laurier L.
River
Lac Bellevue
L. Eliza
Saskatchewan
North
0
10 Km
6
D1,2,3
5
D4,5,6
1
7
9
2
D7,8
8
46
12
15
16
11
10
3
13
17
18
4
20
21
Sites
O Fabric
• Texture and lithology

Fig. 15 Location of Sample Sites

Freschauf (1971) have demonstrated the usefulness of microfabric analysis to studies on the internal structure of tills and, therefore, this technique was applied to orientated blocks of till taken at each fabric site. The samples were obtained by excavating a block of till and preparing a horizontal upper surface. A north orientation arrow was then placed on this surface. The block was removed from the face of the roadcut, carefully trimmed to a cube of side 5 cm, wrapped in tissue paper, and stored in labelled cardboard containers. In the laboratory each microfabric sample was air dried and impregnated with a polyester resin. The procedures were those outlined by Boul and Fadness (1961), Innes and Pluth (1970), and Ashley (1973). Thin sections cut parallel to horizontal and vertical planes were made from 18 of the cubes. The slides cut parallel to the horizontal plane were used to obtain the azimuth of the silt and fine sand grains in the till, while the slides cut parallel to the north-south orientated vertical plane were used to obtain plunge angles. A petrographic microscope was used to measure one hundred particles on each slide.

Both the macrofabric and microfabric data are presented using mirror image circular histograms, or rose diagrams, with 10° class intervals. The macrofabric data are also presented in equal area contour diagrams (Kamb, 1959) drawn by means of a program designed by Corbato (1966). The circumference of each circular diagram is calibrated in azimuthal degrees, and the perimeter represents 0° plunge with a plunge of 90° represented at the centre of the circle. A counting circle which represents 3% of the total area of the circular net was drawn about a set of predetermined grid points on the hemisphere and the number of data points in each area were recorded as a percentage of the total number of points in the diagram.

A 2% contour interval was chosen for display.

The plunge data for the microfabrics, which is presented on half-circle rose diagrams with 10° classes, illustrates the distribution of plunge with respect to the up- and down-glacier directions. All fabric diagrams are included in Appendices A and B.

The macrofabric data were first analyzed using the methods of Watson (1956) and Steinmetz (1962). A vector mean orientation ($\overline{V}$) was calculated for each fabric distribution with each pebble representing a unit vector. The vector strength (R) was calculated for each fabric distribution following Steinmetz (1962). The macrofabric data were additionally analyzed using the eigenvector methods given in Mardia (1972). This procedure gives the principal eigenvectors and eigenvalues for each fabric distribution and the distribution form, bipolar or girdle.

In the analysis of macrofabrics, the largest eigenvector V_1 shows the axis of maximum clustering and represents the mean axis, while V_3 shows the direction of minimum clustering and is orthogonal to the V_1-V_2 plane. The degree of axial clustering about V_1 and V_3 is given by S_1 and S_3. S_1 measures the strength of clustering about the mean axis, while S_3 is inversely proportional to the degree to which axes lie within the preferred plane of the fabric (Lawson, 1979). The vector mean ($\overline{V}$), calculated from Steinmetz (1962), also represents the mean orientation for each sample. The strength of this vector mean is indicated by the value R. These variables, which are shown in Appendix C, are the principal ones used to characterize the macrofabric data.

The microfabric azimuthal data were statistically analyzed by comparing the distribution of grain azimuths, each grain representing a unit vector, to a von Mises distribution (Harvey and Ferguson, 1976). The von Mises distribution describes the distribution of a set of data about the vector mean of the sample. Comparison of the estimated von Mises distribution and the observed distribution allows a Chi-square value to be calculated for each sample. If the Chi-square value is less than the Chi-square value for 15 degrees of freedom at a selected level of significance of 5%, the sample is said to fit the von Mises distribution, and the calculated vector mean is accepted as a measure of the central tendency of the distribution. Fortran subroutines developed by Harvey and Ferguson (1976) were used to analyze the microfabric data.

The microfabric plunge data were tested using a significance of proportion test (Bruning and Kintz, 1968). The resultant, Z, is compared to a standard normal curve which has a critical point of 1.645 at a 5% significance level. Any microfabric sample with a Z value of less than 1.645 is considered to have no significant preferred up- or down-ice plunge. All microfabric statistical data are given in Appendix D.

Till Texture and Lithology

A sample of approximately 150 grams of till was collected at each fabric site for textural and lithologic analyses. Textural analysis was by means of hydrometer and sieving (Means and Parcher, 1964). The lithologic data, which are shown in Appendix F, were obtained from a microscopic examination of the 1-2 mm sand fraction retained during the sieving procedure. A carbonate staining method developed by Friedman (1959) was used to differentiate carbonate and crystalline grains.

Additional samples for textural and lithologic analysis were obtained from numerous roadcuts throughout the study area, and from auger holes drilled in the crests and troughs of three flutings. Further till textural and lithologic information was obtained from the Quaternary Geology Group of the Alberta Research Council. All textural results are given in Appendix E.

Chapter IV

Presentation of results and their interpretation

Introduction

Several theories concerning ice-moulded streamlined landform genesis have been mentioned previously. These depend on the ice flow characteristics and the availability and type of supraglacial, englacial and subglacial materials. Since there is no feasible way of observing the proposed formative mechanisms directly, a fruitful approach to test their validity is examination of the resultant materials and forms. So analysis of till fabric, texture, and lithology were performed by the methods outlined. As well, the characteristics of stratified deposits and bedrock were studied.

Description of Field Sites

Most of the sections studied show the single till discussed previously. Some contain bedrock. In a few, glaciotectonic activity is indicated by the reversal of the normal stratigraphic sequence of till and stratified deposits overlying bedrock, and the truncation of otherwise undisturbed beds of stratified deposits. In some sections (eg. Twp. 56, R.6, Sec. 10, L.S.D. 13, W/4th) a sharp, clear contact exists between a till layer which overlies beds of fine to medium sand dipping at approximately 60°. The sand beds are truncated sharply by the till without local disturbance, in the vicinity of the contacts, of the stratified layers. The stratified deposits must have been frozen and moved by the ice through a thrusting or folding mechanism. Similar evidence of glaciotectonics can be found in a number of gravel pits, located immediately north of St. Paul, where an unconformable contact occurs between gravel and sand beds and an overlying till. The absence of intermixing between the till and stratified deposits, and the steep angles of dip of the stratified layers, sometimes almost vertical, are taken as further evidence of the displacement of these beds by glacial thrusting during frozen-bed conditions.

A large bedrock thrust block southeast of St. Paul (Twp. 56, R. 8, Sec. 36, L.S.D. 4, W/4th) shows a sequence of shale, clay ironstone, and sandstone overlying beds of till, and fine to coarse sand. A landform has been created which is dominated by bedrock but with till and stratified deposits to the lee, and coarse sand and gravel deposits on the stoss side. The volume of lee-side deposition is much greater than that of the stoss-side sands and gravels. A complex sequence of bedrock, till, and stratified deposits is found in the lee of the bedrock knob. A greater amount of material is to be expected on the lee side because of the probable existence of a low pressure zone at this location during deposition. Again, in this section, frozen-bed conditions are indicated by the uncomformable contacts between stratified beds and other deposits. The reversal of the normal stratigraphic sequence is explained by glacial thrusting. Without a more detailed investigation of these sections only the general conclusion of widespread glaciotectonic activity under frozen-bed conditions can be reached.

Macrofabric Analysis and Interpretation

If the pattern of a number of till fabrics bears a close relationship to a landform and the till fabric is assumed to be of depositional origin, then a common origin may be considered for both.

The landform is, therfore, probably depositional. However, if there is no such clear relationship or if the materials within the landform are not compatible with deposition from ice, then an erosional hypothesis may be favoured. The complex 'herring-bone' fabric described by Shaw and Freschauf (1973) and Shaw (1975) is expected to be present if the transport and subsequent deposition of till has occurred because of the existence of differential pressure zones in the ice and parallel to the direction of ice flow. These pressure zones may cause secondary flow cells (Shaw and Freschauf, 1973). Such pressure zones may be created by the development of a low pressure zone in the lee of a glacial thrust block (Moran et al., in press), or in the lee of any resistant block of subglacial material.

Site 1 macrofabric diagrams, with the exception of 1C, (Appendix A) show an overall parallel to fluting crest orientation. The V_1 azimuth for each diagram, except 1C, (Appendix C) are closely aligned with the main direction of regional ice flow direction, which is from 325°. This direction is also approximated by the vector means for each distribution. The fabric at site 1C shows low values for S_1 and R, indicating non-preferred orientations.

The preferred up- or down-ice inclinations for the macrofabric sites were determined on the basis of the primary glacier flow direction (from 325°). Any V_1 (Appendix C) which has an azimuth of between 236° and 54° is considered to have an up-ice inclination. A V_1 which shows an azimuth of between 56° and 234° has a down-ice inclination. This is assuming, in both cases, that some inclination of the V_1 plane is present. Also, a V_1 azimuth at right angles to the glacier flow (55° or 235°) is considered to have no preferred up- or down-ice inclination. The plunge of the major axis is given in Appendix C (V_1, plunge).

Four of the site 1 fabrics (1B, 1D, 1E, 1F) have an up-ice inclination to their major axes (Appendix C). The fabrics at sites 1A and 1C have down-ice inclinations.

Shaw (1980) has shown that tills in drumlins and large-scale flutings are often of melt-out origin. It will be shown later that the tills in the study area, ice-moulded landforms, are also probably of melt-out origin. Although no work has been done on quantifying the relationship between flow rates and preferred orientation of clasts in tills deposited by modern glaciers it is reasonable, at this stage, to suggest that melt-out tills whose fabrics have parallel orientation and high vector magnitudes are associated with ice having relatively high flow rate and consistent flow direction. Thus, the bipolar distributions of site 1 (1A, 1B, 1D, 1F) are taken to indicate that the process producing preferred orientation were strong at the sites where these distributions occur, whereas the girdle distributions (1C, 1E) indicate less powerful processes producing orientation, or subsequent disturbance, occurred at these sites. These patterns are well illustrated by the respective rose diagrams (Appendix A). Bipolar fabrics generally show unimodal rose diagrams while girdle fabrics show multimodal rose diagrams. Also, the V_1 azimuth of each bipolar site is aligned closely with the primary 10° modal class of the respective rose diagram (Appendices A and C).

The combined macrofabrics at site 2, the drumlin, show a 'herring-bone' rather than a unimodal pattern (Appendix A). The fabric distributions at sites 2A and 2B, which are bipolar, and 2E, a girdle distribution, have V_1 azimuths which closely parallel the drumlin crest. The fabric at site 2C, a girdle distribution, and that at site 2D, a bipolar distribution, have V_1 azimuths and vector means (Appendix C) which are rotated clockwise from the main drumlin axis. That is, the angle between the main drumlin axis and the preferred direction is acute in the clockwise direction. The fabric at site 2F shows a girdle distribution and the angle between the main drumlin axis and the V_1 azimuth is acute in the anticlockwise direction. The divergence of the V_1 azimuth from the regional glacier flow direction in this case is 67° (Appendix C).

Most of the site 2 macrofabric distributions have major axis inclinations up-ice, with relatively large values at sites 2A, 2B, and 2E. The up-ice plunge plus the evidence of an ice flow direction parallel to the crest at the drumlin center (sites 2A and 2B) and an oblique ice flow direction at the margins, with convergence towards the drumlin center (sites 2C, 2D, and 2F), are predicted under the secondary flow hypothesis of Shaw and Freschauf (1973).

The macrofabrics of samples from site 3 do not show the pattern predicted under the hypothesis of Shaw and Freschauf (1973). The central fabrics 3A and 3B, which show bipolar distributions, have principal eigenvector azimuths and vector means which parallel the fluting main axis. The fabric at site 3D displays a strong asymmetric bipolar distribution having a V_1 azimuth and vector mean rotated clockwise from the fluting main axis. Secondary ice flow towards the fluting center could be implied from this trend although alternate causes such as post-depositional disturbance are plausible. But it is difficult to imagine slumping creating the high S_1 value obtained. The fabrics at sites 3C, 3E, and 3F have modal classes which are almost transverse to the fluting main axis. The girdle distributions of the fabrics at 3E and 3F give no indication of a consistent ice flow direction. However, the transverse, bipolar distribution at 3C could have originated through a secondary ice flow, without a down-glacier component. In fact, the fabrics at both 3C and 3D, which are located on the same side of the fluting, could have been formed by a dominant secondary ice flow. A similar, though less convincing argument could be applied to fabric 3F. Slumping would not be expected to create the high S_1 values and the low S_3 values of distributions 3C and 3D.

The major planes of the distributions at sites 3A, 3D, and 3F are inclined down-ice, the plane of the fabric distribution at site 3B is inclined up-ice, and the fabric distributions at sites 3C and 3E have no preferred up- or down-ice inclination due to their transverse orientation (Appendix C). In addition, the almost transverse orientation of fabric 3F and its weak girdle distribution cast doubt on the utility of a down-ice classification. Also, if the formation of the fabrics at sites 3C and 3D by a transverse ice flow is accepted, then the assignment of a down-ice inclination relative to primary ice flow becomes meaningless.

The fabric diagrams of the drumlinoid, site 4, show a wide array of vector trends (Appendices A and C). The fabric at site 4D shows a girdle distribution, and that at site 4E shows a bipolar distribution and both have V_1 azimuths aligned parallel to primary ice flow direction. The V_1 azimuths of the fabrics at sites 4A, a girdle distribution, and 4B and 4F, bipolar distributions, are rotated anticlockwise from the main axis of the landform. The V_1 azimuth of the fabric at site 4C shows a girdle distribution and is rotated clockwise from the main axis of the landform. In each case the vector mean approximates the V_1 azimuth.

The rose diagrams for site 4 fabrics (Appendix A) give a two-dimensional impression of the vector trends present. They depict a general trend of ice flow from between 290° and 335° which is contradicted only by the diagram for site 4C. This general northwesterly flow pattern could represent some local asymmetry in the flow pattern. This idea is clearly conjecture and could never be substantiated, however it is difficult to imagine a post-depositional mechanism such as slumping, causing such a systematic trend.

All of the major axes of fabrics at site 4, with the exception of 4B, have up-ice inclinations relative to a regional ice flow direction of 325°. The major axis of fabric 4B has a down-ice inclination.

The macrofabric diagrams for site 5 suggest fabric formation under complex ice movements. Fabrics 5A, 5C, and 5F have girdle distributions, however fabric 5A has a quadripolar, bimodal distribution. Following Glen et al, (1957) this bimodal distribution at site 5A could have resulted if some of the pebbles were rotated about their 'A' axes during transport, whilst others were rotated about their 'B' axes. However, we can only speculate on the exact mode of transport when the only information available is the resultant fabric.

If fabric 5A is interpreted to show an orientation parallel to the fluting crest, then four of the site 5 macrofabrics preferred orientations, excluding fabrics 5D and 5F, are approximately parallel to the primary ice flow direction. Fabrics 5D and 5F have preferred orientations transverse to the primary ice flow direction.

No overall preferred up- or down-ice inclination of major axes is shown in the site 5 macrofabrics. Fabrics 5A and 5C have an up-ice plunge, and fabrics 5B, 5D, 5E, and 5F have a down-ice plunge.

At section 6, the section cut parallel to the fluting crest, it was possible to obtain only two fabrics, because of the limited exposure. Both fabrics 6A and 6F have girdle distributions, which have preferred up-ice inclinations of the major axis. The V_1 azimuth of fabric 6A is rotated slightly clockwise from the fluting main axis, but the vector mean is parallel to this axis. This fact and the girdle distribution may indicate a less powerful orientation mechanism at this location. The V_1 azimuth of fabric 6F and the vector mean are rotated anticlockwise from the fluting main axis according to the expectation under secondary ice flow at this location.

The overall conclusion that can be made from the macrofabrics is one of complexity. Fabrics at sites 1, 4, and 5 display a preferred parallel, or near-parallel, to primary ice flow direction. Fabrics at sites 2, 3, and 6 display a parallel to primary ice flow orientation beneath the landform crests, and oblique orientations converging towards the crests in a downglacier direction. The fabrics at site 4 suggest a complex primary and secondary ice flow regime, but the 'herringbone' pattern predicted by Shaw and Freschauf (1973) is not evident.

As suggested earlier, the distribution patterns of the three-dimensional contour diagrams is interpreted to give some indication of ice flow intensity. Stronger ice flow is expected to create well-formed bipolar distributions of pebble azimuths The only macrofabrics which show any consistency in this regard are those from location B which all exhibit a bipolar distribution. This suggests that stronger flows or more consistent directions of flow were associated with the emplacement of material in the central and basal part of the landform than elsewhere.

The rose diagrams show an instructive overall two-dimensional fabric pattern. Since the 10° modal class of the individual rose diagrams is usually closely aligned with the associated V_1 azimuth and pebble dips are low, the rose diagrams may be used to give a strong visual impression of fabric patterns for each landform. Additionally, the composite rose diagrams (Appendix A) give a strong visual impression of an overall 'herring-bone' pattern. The A and B fabric site diagrams show modes parallel to the primary ice flow direction. The C, D, E, and F fabric site diagrams show convergence towards the centers of the landforms in a down-glacier direction.

Shaw and Freschauf (1973) presented a similar set of composite rose diagrams for their macrofabric data obtained from flutings in the Athabasca area of Alberta. Their composite diagrams also show a 'herring-bone' pattern which they interpret as evidence of the presence of both primary and secondary flow in the formative ice. The composite macrofabric rose diagrams for the streamlined landforms of the St. Paul area support this general conclusion.

Microfabric Data Analysis

The two dimensional orientation and dip diagrams for the microfabric data are shown in Appendix B. Since only two-dimensional axial data, which cover 0° - 180°, are available from microfabric measurements contour diagrams cannot be constructed. The microfabric statistical data are given in Appendix D.

The microfabric orientation diagrams show a much more consistent trimodal fabric at each site that the associated macrofabric samples. Microfabric site 1 samples show a clear trimodal fabric pattern. Fabrics 1A and 1B have vector means which parallel the fluting crest and primary ice flow direction. Fabrics 1C and 1D have vector means which are rotated clockwise from the fluting crest, suggesting secondary ice flow. The vector means of fabrics 1E and 1F are transverse to the fluting crest. All site 1 distributions approximate the von Mises distribution (Harvey and Ferguson, 1976).

The site 3 microfabric orientation distributions display a less consistent fabric pattern than the site 1 distributions. Fabric 3A shows a preferred direction parallel to primary ice flow direction, but fabric 3B shows a pronounced parallel mode and a broad approximately transverse mode with a consequent low vector strength. This low vector strength implies the sample does not have a strong preferred orientation. Fabrics 3C and 3D conversely have relatively high vector strength values and preferred orientations oblique to the fluting crest orientation. Fabrics 3A, 3B, 3C, and 3D all satisfactorially fit a von Mises distribution, however fabrics 3E and 3F do not. The failure of fabrics 3E and 3F to fit a von Mises distribution accords with the absence of preferred orientations in macrofabrics 3E and 3F.

When viewed in combination, the microfabric site 5 fabrics show a clear fabric pattern of the 'herring-bone' type noted by Shaw and Freschauf (1973). The fabrics located at the fluting crests, 5A and 5B, display a parallel to primary ice flow orientation. Fabrics 5C and 5D show an orientation rotated clockwise from the fluting crest, while fabrics 5E and 5F show an orientation rotated anticlockwise from the fluting crest. Thus, assuming preferred orientations parallel to local ice flow direction, a flow which converged towards the fluting crest is indicated by the fabrics at sites 5C, 5D, 5E and 5F. The vector strength values are high for every sample, except 5A. All site 5 samples fit a von Mises distribution.

The significance of proportion test (Bruning and Kintz, 1968) used to test the microfabric plunge data shows that all samples have a significant up-ice plunge, except for samples 3B and 3D in which no preferred up- or down-ice plunge is evident. A dominant up-ice plunge is predicted under Shaw and Freschauf's (1973) secondary flow hypothesis since the flow in secondary cells must rise at convergences.

The consistency of the microfabric orientation and plunge data compared to the associated macrofabric data is difficult to explain. One possible explanation may center around the deglaciation conditions during deposition of the glacial debris. As has been suggested previously, deglaciation probably occurred under cold, arid conditions, and deposition occurred through extremely slow basal melt-out. Under these circumstances very little post- or syndepositional disturbance of the primary orientations in the debris is expected (Shaw, 1977). However, the layer volume of individual pebbles compared to the sand and silt grains may cause them to be more susceptible to disturbance. Boulton (1970b) and Evenson (1971) suggest that pebble concentration is an important factor in the preservation of primary orientation. High pebble concentrations may cause a 'cross-fabric' to be formed (Evenson, 1971), or simply a weakening in the strength of preferred orientation (Boulton, 1970b). A qualitative estimate of pebble concentration in the study area sections indicated a relatively high percentage of pebbles (ie. 2% to 3% by area). This was readily apparent during macrofabric measurement which was faciliatated by the abundance of pebbles. Thus, the pebble density may have been an important factor during the depositional phase of the formation of the study area landforms.

An additional factor which could influence both the micro- and macrofabric is the possibility that the debris was transported and deposited as a frozen block of subglacially derived material. If this occurred the till fabric would be inherited. This possibility is especially applicable to the study area, where there is evidence of major, local glaciotectonic activity.

Till Textural and Lithologic Analyses

Lithologic and granulometric analyses were carried out on samples obtained from sections and auger drill holes. Most analyses performed on the till samples show a remarkable similar textural and lithologic composition (Figure 16, Appendices E and F). The average textural percentages and their standard deviations are: sand, 34.0, 7.5; silt, 26.5, 5.6; and clay 39.5, 6.7. The average lithologic percentages and their standard deviations are: crystalline, 93.0, 3.3; carbonate, 4.7, 7.3; and local clastics, 2.2, 6.3. There is no significant dominance of limestones or dolostones in the carbonate category. The average textural composition shows reasonably similar proportions of sand, silt, and clay, but with the clay percentage being slightly higher than the other two.

The auger holes drilled in fluting ridges and adjacent troughs

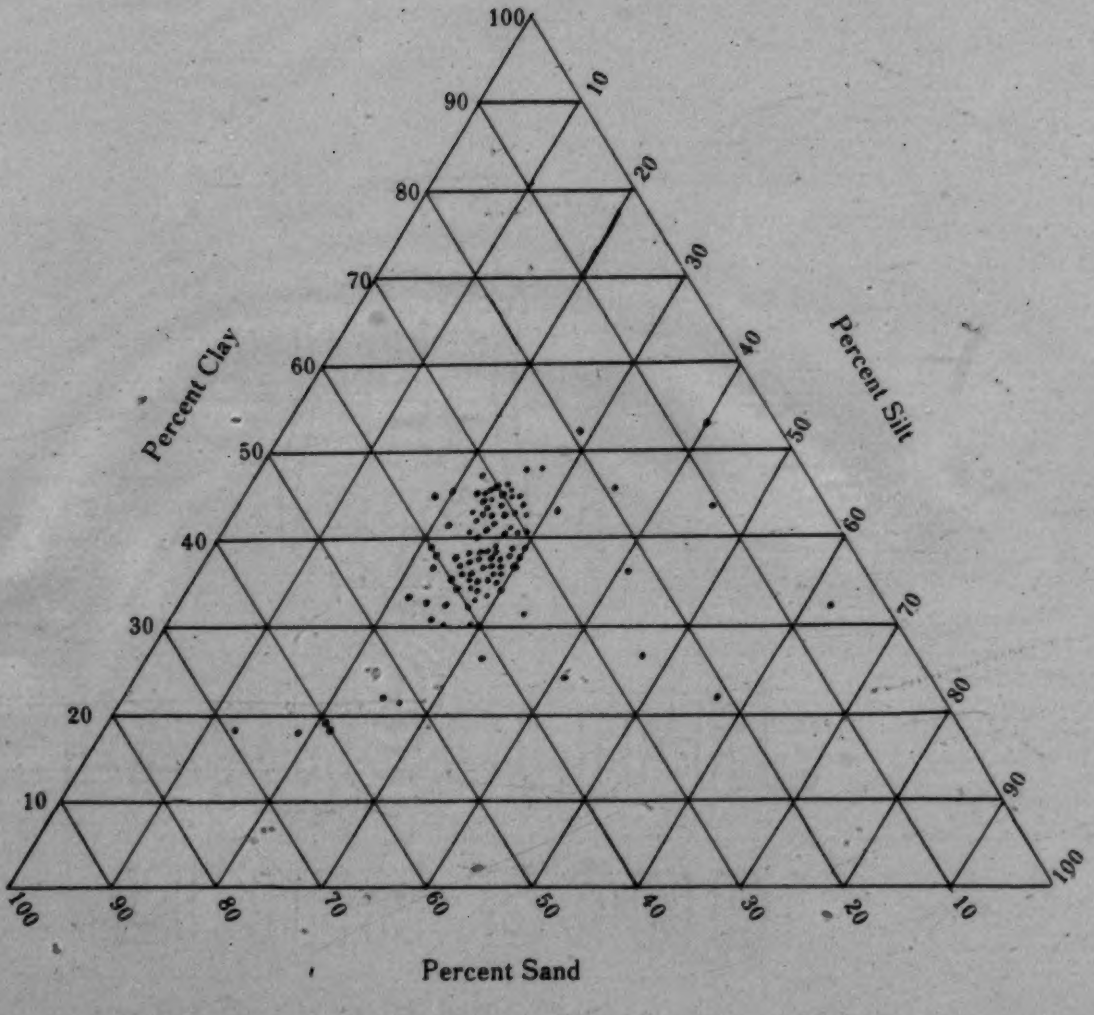

Fig. 16 Textural Triangle for Till Samples

also show a uniform till texture. The same till was present throughout all of the landforms drilled, implying the material for the flutings was derived from the same source area and formation occurred during only one ice advance. The upper 0.5 m to 1.0 m of the holes drilled in the fluting troughs showed a clay which may have been deposited through a washing of fines from the adjacent ridges after deposition of the till. Any sandy material left on the fluting ridges may have been removed by aeolian activity, or incorporated during soil development.

A slightly sandier till was found approximately 7 m to 10 m below the base of some of the flutings, that is, at a total depth of 15 m to 18 m. This may indicate the presence of a different till. In some locations the two till units were separated by about 0.5 m of medium to coarse sand. This sand layer has been found at approximately the same depth in auger holes drilled by the Alberta Research Council. No evidence is available yet to indicate whether or not the lower till unit is a product of a separate ice advance, or the extent of the two units.

Examination of Fluting Wavelength

Fluting transverse wavelengths were obtained from 1:63,360 scale aerial photographs. This procedure was chosen over spectral analysis because of the difficulty in recognizing the low (≤ 1m) flutings by ground survey. In the area of low flutings northwest of Elk Point a somewhat regular pattern is discernible on the air photos but no consistent transverse wavelength is evident. The minimum ridge crest to ridge crest distance is approximately 50 m, but spacing may range up to 775 m and a constant crest to crest distance is never maintained for more than three flutings (Fig. 17). Three moderately defined wavelengths are shown for these long, low flutings: one at about 100m; one at 225 m; and one at 300 m. Also, a less well-defined wavelength is evident at approximately 450 m. The single occurrence at 775 m represents an isolated fluting.

In the areas of high flutings (≈ 8 m) northwest and southeast of St. Paul there is a random distribution of the landforms with the most prevalent ridge crest to ridge crest distances ranging from 100 m to 350 m (Fig. 17). The single occurrences at approximately 650 m and 750 m are indicative of isolated flutings. A case could be made for a somewhat ill-defined fluting wavelength of 100 m to 350 m, however the relatively narrow fluting wavelength range of 90 m to 125 m found by Gravenor and Meneley (1958) for the North Battleford, Saskatchewan region is more indicative of a regularly-spaced fluting distribution. In contrast the wide distribution of wavelengths present among the large flutings of the Lac la Biche field, and the relatively short lengths of the flutings, cause the field to resemble a random 'basket of eggs' appearance.

Gravenor and Meneley (1958) also studied the Cold Lake area flutings which they described as 'elongate drumlins', a description which adequately describes many of the St. Paul area large-scale flutings. In this area they found a primary wavelength of 90 m to 125 m and a secondary wavelength of 180 m to 215 m. Neither of these wavelengths is present in the St. Paul area large-scale flutings, although the landforms present in both fields are morphologically similar and both are probably products of a late Wisconsin ice advance.

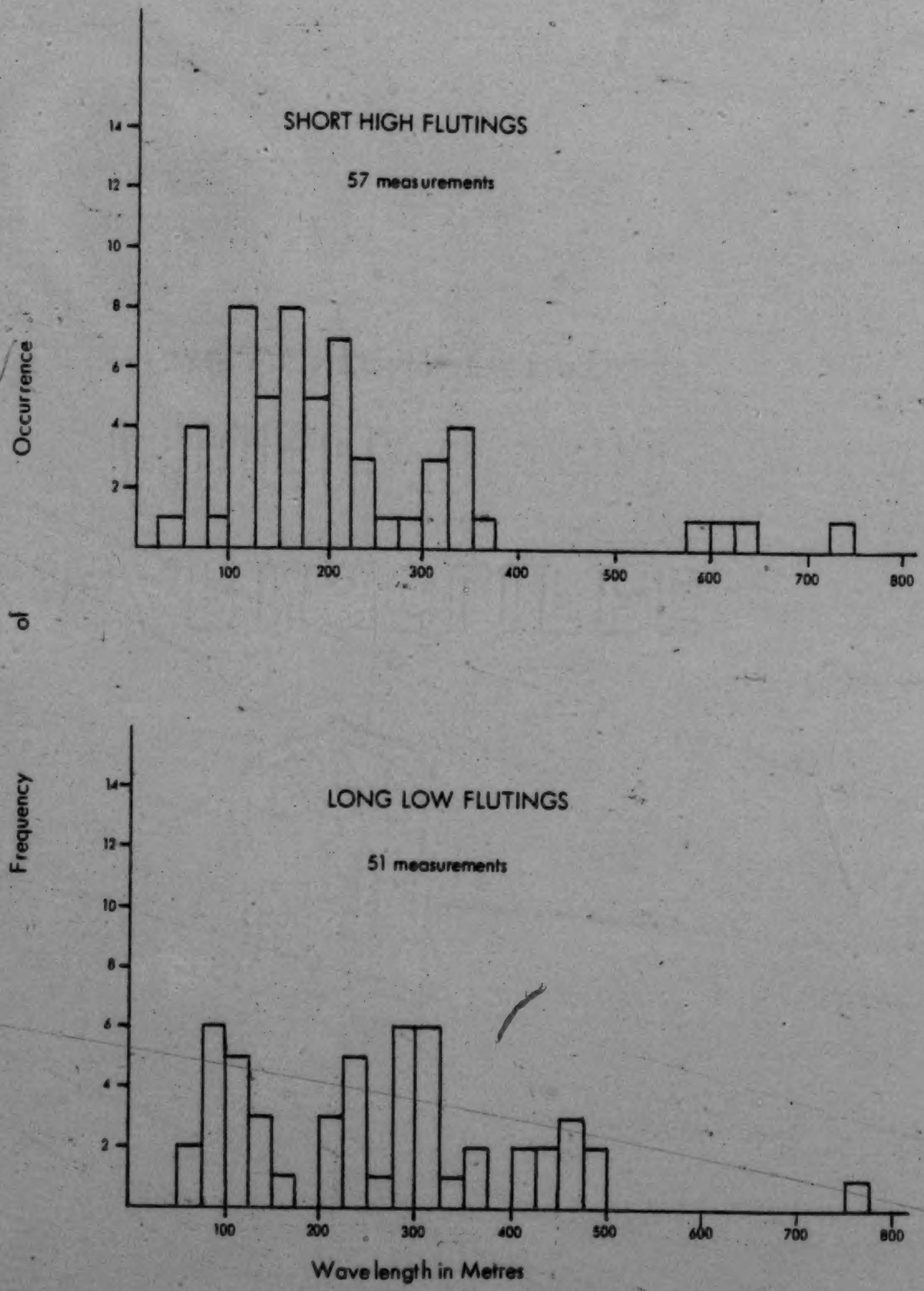

Fig. 17 Frequency of Flutings vs. Transverse Wavelength Classes

All of the fluting fields studied by Gravenor and Meneley (1958) have one characteristic similar to the long low flutings near Elk Point. All of these regions have a preferred wavelength of approximately 100 m, although in the case of the Lac la Biche field this is only one of four poorly-defined wavelengths measured. Generally the fluting fields investigated by Gravenor and Meneley (1958) show a better defined fluting wavelength than either the long, low flutings or the large-scale flutings of the Lac la Biche field. However, this overall lack of a significant wavelength in the Lac la Biche field agrees with the results of Freschauf (1971) for the Athabasca, Alberta area.

The random pattern of the large-scale flutings of the Lac la Biche field is not unexpected since glacial thrusting is considered a dominant formative mechanism in the region's fluting development. The thrusting of blocks of subglacial sediment, which hypothetically are eventually moulded into flutings, is dependent upon the variable factors discussed earlier. A regular sequence of thrust block emplacement is not expected, therefore a regular fluting wavelength is unlikely.

Summary

Examination of the till macro- and microfabric diagrams gives strong support for the existence of composite ice flow in the study area during the formation of the Lac la Biche fluting field. The 'herringbone' fabric detailed by Shaw and Freschauf (1973) and Shaw (1975) is noted in some of the fabric diagrams shown in the appendices, especially the microfabrics.. Additionally, the evidence of glaciotectonics and frozen bed conditions found in field sections supports the possibility of thrusting, as proposed by Moran _et_ _al_. (in press), as the initiating mechanism for some of the streamlined landforms. The 'herring-bone' fabric may be related to the lee deposition which occurs as a result of low pressure on the downstream side of thrust blocks causing convergent flow and secondary cells (Shaw and Freschauf, 1973).

The existence of only one till in the auger holes drilled through flutings in the study area indicates these landforms were formed during a single ice advance, contrary to the theory of Gravenor and Meneley (1958), and reduces the validity of an accretional hypothesis postulated by Alden (1918) and Fairchild (1929).

The lack of a consistent wavelength pattern agrees with the variable flow conditions which are thought to occur in large ice sheets. An irregular pattern seems more realistic because of the many variables which govern ice sheet movement (eg. bed conditions, temperature regime, pore-water pressure, ice thickness, pre-glacial topography, and ice velocity). Also, if the flutings originate at thrust blocks then they depend on those local conditions which cause thrusting (Clayton and Moran, 1974; Moran _et al_., in press), consequently they are not expected to be regularly arranged.

CHAPTER FIVE

Conclusions and Previous Hypotheses

Introduction

The genesis of streamlined landforms in the St. Paul area may be explained by several different, and yet related hypotheses. The four which are emphasized here are those of Gravenor and Meneley (1958), Smalley and Unwin (1968), Shaw and Freschauf (1973), and Moran *et al.* (in press). The relevance of each of these hypotheses to this study area will be examined, as well as their compatibility. An important feature is the increasing emphasis on a composite process of erosion and deposition, rather than concentrating on mechanisms based solely on erosion or deposition, which hampered the progress of earlier attempts to explain drumlin formation. Also, the role of ice flow characteristics and glacier mechanics is stressed in most recent articles. Geomorphologists are beginning to lean heavily on glaciological theory where this is applicable to glacial landform development. However, the mistake of placing too much emphasis on a single component of any theory must be avoided, since other factors, such as type of material, topography, climatic conditions, and time may be equally important to these studies.

No previously proposed theory adequately accounts for the features studied in the St. Paul area. However, as will be seen, a combination of the ideas discussed earlier satisfactorily explains the presence of the landforms examined. In the following discussion of concepts only the salient points of each theory will be presented, as a more detailed summary of the papers has been given earlier.

Smalley and Unwin (1968)

The dilatancy mechanism proposed by Smalley and Unwin invokes the effect of glacier flow on subglacial materials. Basically, the tangential shear exerted by the ice causes a water-saturated material to expand and there is considerable resistance to initial deformation. At higher levels of shear a fully dilated material deforms subglacially. As the shear stress drops, parts of the deforming material collapse and become static, and the remainder deforms around these static parts. These static mounds of debris will then be moulded by flowing ice and debris.

Smalley and Unwin define three levels of basal stress: A, B, C where A > C > B. Stress in a range < B is too low for deformation to occur. Stress > A causes continuous deformation. In stress range C deformation continues provided the material has been dilated at A. Stresses continuously fluctuate from > A to < B near the margin of an ice sheet, thus, should material be dilated at a stress > A, the first parts of this debris experiencing stress that drops through range C, to a level < B, will form residual mounds which will be moulded into drumlin shapes by other debris deforming around them.

Smalley and Unwin's mechanism is based on a number of specific conditions which must be met before dilatancy can occur. These include an unfrozen bed (ie., wet-based conditions), a concentrated dispersion of boulders in a clay-water matrix, a specific sequence of stress values, and the assumption that once the drumlins are formed, they are not overridden by ice with stress > A. Smalley and Unwin argue that drumlin formation occurs in a narrow band parallel to and near the final ice margin. This formation occurs in the final stages of ice advance, otherwise the drumlins would be obliterated by progressively higher stress levels as the ice advances. They postulate an inverse relationship between drumlin density and distance from the ice margin.

A number of important differences exist between the configuration and landform density of the Lac la Biche field and those predicted by Smalley and Unwin. The extreme length of the field (≈ 390 km) and its narrowness (≈ 25 km) contradict the dilatancy theory which postulates the formation of a short, wide field proximal to the final ice terminus position. Secondly, drumlin and fluting density in the Lac la Biche field is highest at the point of origin near Lac la Biche, not near the terminal position northeast of North Battleford as predicted by Smalley and Unwin. Another aspect which is incompatible with the Smalley and Unwin model is the widespread occurrence of folded and faulted material which indicates frozen-bed conditions, and are not expected under their model.

The long, low flutings which begin southeast of St. Paul may be an exception to the widespread occurrence of frozen-bed conditions. No evidence of glaciotectonic activity was found in this part of the field which may indicate that thawed-bed conditions existed, thus, the Smalley and Unwin theory may be relevant to these landforms. However, the absence of glaciotectonic structures does not eliminate the possibility of frozen-bed conditions.

Till fabric patterns are a property of drumlins not mentioned in detail by Smalley and Unwin. Assuming their theory, once the mound has become static a differential pressure system will be set up between a high pressure stoss side, and a low pressure lee side. Debris being transported by the ice will converge on the low pressure area, and a 'herring-bone' type fabric pattern will develop as material moves in from either side of the mound. Fabrics at the centre of the landforms should show a strong parallel to crest orientation where the two flow systems converge and flow parallel to the main direction of ice flow. However, this possibility involves a considerable addition to the initial concept of Smalley and Unwin.

The material compostion of the study area drumlins and flutings is essentially that proposed to be necessary for dilatancy to occur. A slightly higher percentage of clay, than sand or silt, was found, although the frequency of large boulders was low.

The differences between the study area landforms and those predicted by Smalley and Unwin (1968), especially the size and layout of the field, and basal thermal conditions, cause the dilatancy theory to be basically inapplicable in the St. Paul area. This is contrary to the findings of Crozier (1975) who supported the Smalley and Unwin model with evidence from the Peterborough drumlin field. Parts of their model may be used in conjunction with other theories for the St. Paul area. For example, if their initial static mounds cause subsequent shearing and lee deposition the theory is compatible with Gravenor's (1953) modified erosion hypothesis and may be applied to some of the streamlined deposits found within the study area.

Gravenor and Meneley (1958)

Gravenor and Meneley's paper is particularly relevant to this study because it concerns glacial flutings in Alberta and part of their paper specifically concerns the southeast, or distal part of the Lac la

Biche field. Their study incorporates an extensive examination of fluting distribution, wavelength, fabric, and origin. Gravenor and Meneley's thesis on fluting origin is straightforward. This was one of the first papers to relate fluting development to basal conditions in the ice, postulating that formation occurs because of "alternating parallel high and low pressure zones at the base of the ice," (p.727). Material is transferred from high pressure zones to low pressure zones where the ice becomes debris-clogged, and deposition, by melt-out from stagnant basal ice, occurs. More material may then be plastered onto these cores by active ice. This is similar to Smalley and Unwin's (1968) theory, in that water-saturated basal debris is deposited as a resistant block at the base of the ice, and is eventually moulded into a drumlin shape.

Further evidence of residual mounds of basal debris being formed into drumlins and flutings has been presented by Lundqvist (1970). He postulates a gradational series of landform assemblages from Rogen moraine through to drumlins, suggesting that drumlins are an extension of Rogen moraine development. Aario (1977) expanded upon this idea by suggesting that the complete range of landform assemblages is: hummocky moraine → Rogen moraine → drumlins → flutings. He further postulated spiral flow, caused by differential basal pressure zones, to be the dominant formative force for the drumlin and fluting assemblages. No Rogen moraine were found in the St. Paul study area to corroborate this theory, thus reducing its relevance for this area. However, it should be noted that Shaw (1979) indicates Rogen moraines are formed in zones of compressive flow by buckling; therefore, they may have exactly the same effect as thrust blocks in that they create an initial obstacle.

A point which Gravenor and Meneley's paper shares with most theories on fluting development is the presence of unfrozen-bed conditions, and a water-saturated basal material. A clear distinction must be made here between till transport during wet-based and frozen-based conditions. When the ice is in a thawed-bed state the subglacial debris is a separate entity which is moved by the ice, but not with it as a single unit. During frozen-bed conditions the substrate is essentially part of the glacier and moves with it, as shown in the shear structures present in glacially thrust material. Transport occurs through shearing and plucking of relatively weaker blocks of frozen debris. Since, under frozen-bed conditions the ice and substrate are essentially the same unit, it becomes difficult to define the lower boundary of the ice sheet precisely.

It should be noted the initiation of fluting development by the thrusting of a frozen block of debris does not completely negate Gravenor and Meneley's theory. The transfer of material from high to low pressure zones during the advent of thawed-bed conditions, could occur subsequent to thrusting, especially since the resistant block would create a low pressure lee zone. Also, Gravenor and Meneley's theory is relevant to the long, low flutings found south-east of St. Paul, where no evidence of frozen-bed state was found. Additionally, they propose that strictly erosional flutings in bedrock, as found near Andrew Lake in northeastern Alberta, may be created by the process of preferential erosion in the high pressure bands.

Gravenor and Meneley's microfabric studies on the North Battleford flutings, which are part of the Lac la Biche field, show two preferred orientations, one parallel to the fluting crest, and one oblique to it, at depths less than 3.1 m. They suggest that perhaps, since the lower fabric parallels the trend on the Cold Lake flutings, that is towards the southwest, this fabric was developed during this advance and subsequently covered by the till of the Lac la Biche advance. However, they found no compostional differences between the till at the two fabric locations, and no evidence to suggest more than one till is present. I suggest that Gravenor and Meneley found evidence of the movement of debris from a high pressure zone to the depostional low pressure zone, that is, they described part of Shaw and Freschauf's (1973) 'herring-bone' pattern. However, this is speculation since Gravenor and Meneley do not indicate the planimetric position of the fabrics relative to the fluting.

Their proposal that the Cold Lake advance was earlier than the Lac la Biche one is contrary to the air photo and mosaic evidence which indicates that the two advances were contemporaneous. The curvilinear profile of the Cold Lake flutings shows convergence of the two ice streams. The mosaics of the area of convergence show the Cold Lake flutings merging with the Lac la Biche field rather than being truncated by it (Fig. 9). Wavelength measurements made on the Lac la Biche field near St. Paul differ from those on the North Battleford area flutings by Gravenor and Meneley. No evidence was found for their preferred wavelength of 90 to 125 m (Fig. 17).

An interesting point made by Gravenor and Meneley involves the relationship of topography to glacier flow and fluting development. They concluded that fluting formation is not directly controlled by topography but may be affected by it. A good example of this was found in the Lac la Biche field, just northwest of Lloydminster, where transverse compressional features were found where the ice advanced upslope. As mentioned earlier, the reverse gradient probably produced a zone of compressive flow, causing glaciotectonic activity and the formation of these transverse moraines. Beyond the crest of the slope, east of Lloydminster, extending flow and fluting development were reestablished.

Gravenor and Meneley's (1958) work is a benchmark paper on fluting development as it relates both glacier flow and basal conditions. They propose a mechanism which may account for fluting formation in many areas and is particularly important in this study area. The authors make no attempt to suggest a cause for the differential pressure bands, but they do show that the possibility of their existence is strong, and they also outline an example of how fluting initiation may occur under this theory. Later papers have expanded upon their thesis, and one in particular, that of Shaw and Freschauf (1973), is directly related to it.

Shaw and Freschauf (1973)

Shaw and Freschauf (1973) expanded on Gravenor and Meneley's (1958) theory by describing a flow mechanism to transport material between the adjacent bands of high and low pressure in the ice. They proposed the existence of helicoidal flow cells, analogous to those described by Allen (1964, 1968) in fluvial processes. The flow cells are postulated to occur parallel to main flow, with adjacent cells rotating in opposite directions causing material to accumulate between the converging cells. The combined action of this secondary flow and primary flow causes material to be transported in an oblique down-glacier path, converging at the low pressure zones. It is this converging flow that creates the 'herring-bone' fabric pattern predicted by Shaw and Freschauf (1973) and established by their field tests near Athabasca, Alberta.

Similar field tests performed by this author support the existence of a 'herring-bone' till fabric, especially in the microfabrics, and partially in macrofabrics. The existence of only one recognizable till unit in the drumlins and flutings of the study area, indicating formation during a single ice advance, is also in agreement with Shaw and Freschauf's theory.

Another field test of Shaw and Freschauf's theory was performed by Heikkinen and Tikkanen (1979) in northern Finnish Lapland. An area of drumlins and flutings was examined using aerial photographs, morphometry, till texture, and two-dimensional till fabric analyses. Three of the fabrics taken at sites on the flanks of fluting ridges show a preferred orientation pointing towards the centre of the ridge. Heikkinen and Tikkanen (1979) interpret this as evidence of Shaw and Freschauf's (1973) secondary flow, or Aario's (1977) spiral flow, and suggest that debris was transported from erosional grooves to depositional ridges. They conclude that pressure relations beneath the ice and resultant dynamics of ice movements are the most important factors in drumlin or fluting formation. Topography may be of secondary importance.

The outstanding problem facing Shaw and Freschauf's (1973) theory is to provide a mechanism to initiate formation of the secondary flow cells. One theory which may provide a suitable mechanism is given by Hughes (1976) in which he shows how a polygonal array of dikes created by convection in an ice sheet becomes elongated into helicoidal flow under primary flow. Hughes (1976) indicates that the onset of convection is controlled in part by ice thickness. However, once again we are presented with a theoretical solution almost impossible to verify practically.

Minell (1979) conducted a series of experiments with media of different viscosities in order to model conditions analogous to glacier flow. He found longitudinal ridge surface patterns develop where the overflowing, less viscous medium is accelerated (extending flow) and transverse patterns exist where the overflowing medium is retarded (compressive flow). Additionally, Minell (1979) found transverse folds occur at the peripheries of the material, while "... longitudinal folds appeared in the lee of large obstacles, or on very flat areas..." (p. 31).

In another experiment Minell (1979) exerted pressure on a sand bed with a greased roller, and found longitudinal ridges were best formed when high velocity movements, producing high shear, were introduced. This compares favourably to Doornkamp and King's (1971) work, in which they postulate drumlin elongation is directly related to rapid, constant ice flow.

Minell's (1979) work also has some significance to the St. Paul study area, since his experiments show compressive flow occurs where the medium is constricted and extending flow where the medium is unrestricted. In east-central Alberta, as has been previously mentioned, the convergence of two separate ice streams, the Lac la Biche lobe and the Cold Lake lobe, occurred just northwest of St. Paul (Fig. 9). The combined flow of these two streams was then channeled to the southeast by the presence of two large stagnant ice blocks. It is postulated that at the point of convergence longitudinally compressive flow occurred and immediately down-ice, where the ice was forced between the stagnant ice blocks, the flow became extending.

The area which underwent longitudinally compressive flow now contains a swarm of relatively short, high drumlins and flutings, many of which are directly down-ice of existing lakes, which may be source depressions for the landforms. Down-ice of this region, in the area which probably experienced extending flow and accelerated advance, long, low flutings are now present (Fig. 7). If, as Minell (1979) has suggested, longitudinal folds occur on the surface of a medium during extended flow, these folds would create differential transverse pressure system in the ice setting up Shaw and Freschauf's (1973) helicoidal flow cells, and producing flutings.

Moran et al. (in press) show that compressive flow followed by continued ice advance, as in the zone of convergence in this case, can cause initial thrusting of blocks of basal debris, and a subsequent moulding of these blocks into streamlined landforms. The advent of secondary flow in a compressive flow zone, after plucking has taken place, and if ice advance continues, is a reasonable assumption. The plucked blocks would initiate a differential pressure system, inducing the secondary flow. Also, Minell's (1979) tests showed that longitudinal folds occur in the lee of large obstacles. These folds could also inditiate the secondary flow. Wet-based conditions which are required in the depositional stage of Shaw and Freschauf's theory are assumed to have occurred after thrusting, and during the moulding stage of drumlin and fluting development.

One point where my application of the secondary flow theory disagrees with that of Shaw and Freschauf (1973) and Shaw (1975) is in the time factor. These two papers suggest the helicoidal flow cells need operate for only a short period of time, that is 1.3 years, for the initial fluting ridge development to occur. I postulate that continued ice advance, and maintenance of the lee low pressure zone will preserve the helicoidal flow until the pressure differential no longer exists. Therefore, drumlin and fluting development will occur under a continuous sequence of secondary flows maintained by the basal pressure differential. The landforms are thus created by leeward accretion over a long period of time.

Shaw and Freschauf's (1973) claim that divergent flow near the ice margin causes longitudinal crevassing which may be related to the genesis of secondary flow is inapplicable to this study. Constriction by the two stagnating ice blocks makes divergent flow improbable.

Moran et al. (in press)

The paper by Moran et al., is an expansion of Clayton and Moran's (1974) glacial process-form model. They recognize two types of glacier-bed landform in the plains region of Canada and the United States: glacial thrust blocks and source depressions; and streamlined terrain. The former are said to originate under frozen-bed conditions where high pore-water pressures decrease the shear strength of the basal material to a point less than the shear stress exerted by the ice. This is said to occur near the ice margin where the glacier is relatively thin, and cold conditions occur beneath the bed. Other factors which accentuate the thrusting process are the presence of pre-existing planes of weakness, such as bedding or jointing in the sediment, and buried aquifers which elevate the pore-water pressure and reduce the effective normal stress.

Streamlined terrain may be initiated through erosion of the substrate or smoothing of thrust blocks and lee depostion. Two elements exist here, convergence of volumes of debris in lee zones, which may occur under frozen-bed conditions, and deposition which requires thawing. As mentioned earlier, the transport of glacial debris to the lee of thrust blocks is related to the secondary flow structure and creates the 'herring-bone' fabric pattern described by Shaw and Freschauf (1973).

The size, especially the length of the resultant drumlin or fluting will be directly dependent upon the amount of material available for lee deposition, and the duration and consistency of ice flow direction. A direct correlation could be drawn between the type of resultant streamlined landform and these factors, especially the consistency of ice flow direction. For example, drumlins may occur where the ice flows in short movements of inconsistent direction, or in a zone where there is little debris and a complex spatial transition from frozen-bed to thawed-bed conditions, while glacial flutings may develop under periods of continuous ice flow of constant direction, allowing continuous lee deposition by the maintenance of the oppositely rotating vortices of secondary flow. This idea bears some similarity to the proposal of Doornkamp and King (1971) in which they related drumlin elongation to constant ice flow direction.

The distribution of glacier-bed features in the study area differs somewhat from that described by Moran et al. (in press). Those authors predict that thrust blocks should be found near the margins of ice advances and streamlined terrain further up-glacier. However, in the study area glacial thrust blocks are located both up- and down-glacier of streamlined terrain (Fig. 7). The convergence of the Lac la Biche and Cold Lake ice streams, and the constriction of the large stagnant ice blocks may have been responsible for compressive flow and intense thrusting in the up-ice zone. Thus, Lac la Biche, and the smaller lakes found down-ice of it, may be source areas for the material in many of the landforms found in the Lac la Biche field.

Moran *et al*. (in press) provide an explanation for the initiation of glacier-bed features which is particularly useful in the study area and helps explain similar features found in other prairie areas.

Summary

Each of the theories discussed in this chapter represents a major step towards the explanation of the genesis of glacially streamlined landforms. The concept of high and low pressure zones (Gravenor and Meneley 1958) provides a basis for the theory of secondary flow (Shaw and Freschauf, 1973). This idea, in turn, compliments the hypothesis of glacial thrusting and streamlining proposed by Moran *et al.* (in press). The dilatancy mechanism (Smalley and Unwin, 1968) provides a process for the development of resistant blocks of water-saturated subglacial material in the absence of frozen-bed conditions.

A combination of two of these four papers, Shaw and Freschauf (1973) and Moran *et al*. (in press), seem most powerful in explaining the formation of streamlined landforms in the study area. The thrusting of blocks of basal debris during frozen-bed conditions and the subsequent creation of secondary flow, and streamlining perhaps during the onset of thawed-bed conditions as ice advance continued, goes farther in explaining the formation of drumlins and flutings in this region than any other hypothesis proposed to date.

Chapter VI

Summary

Summary and Conclusions

The principal purpose of this study was to examine a drumlin and fluting field in east-central Alberta and determine the genesis of the landforms. The four theories found to be potentially useful were those of Gravenor and Meneley (1958), Smalley and Unwin (1968), Shaw and Freschauf (1973), and Moran *et al*. (in press). These theories were tested by analysis of the morphology and distribution of the landforms and of the texture, structure, and fabric of the landforming materials. In addition, a glacial history of the area was outlined using field investigations and aerial photographic evidence.

Of the four theories examined those of Shaw and Freschauf (1973) and Moran *et al.* (in press) were found to explain best the landforms in the St. Paul area. A genesis based on the initial thrusting of blocks of basal debris during frozen-bed conditions, which led to the creation and maintenance of secondary flow, and final till deposition by melt-out under wet-based conditions, best explains the genesis of most of the landforms in the Lac la Biche fluting and drumlin field. The creation of secondary flow caused by longitudinal folds in the ice surface may have initiated the formation of the long, low flutings found southeast of St. Paul, in an area where ice flow was longitudinally extending. However, the ubiquitous presence of glaciotectonic features is in agreement with the contention that the thrusting/streamlining process was instrumental in the formation of most of the streamlined landforms.

By accepting the applicability of these two papers a number of other possibilities are precluded except in limited areas. Both the layout of the Lac la Biche field and the density of the landforms contained, conflict with expectations under the dilatancy model. Drumlin and fluting density does not decrease up-ice from the terminal ice advance position, and frozen-bed, not thawed-bed conditions, are considered probable during landform initiation. However, the dilatancy mechanism of Smalley and Unwin (1968) may be capable elsewhere of generating resistant blocks of basal debris during thawed-bed conditions, for example in the Peterborough drumlin field (Crozier, 1975).

The presence of only one till in the drumlins and flutings investigated tends to eliminate an accretional explanation for these landforms. Furthermore, strictly erosional theories (eg. Shaler, 1889) are also applicable, since the till fabrics clearly show lateral transport and deposition.

Theories on the development of small-scale flutings, such as Baranowski (1970), Boulton (1976), and Morris and Morland (1976), are also deemed inappropriate for this area, primarily because of the large contrast in scale between the two types of flutings, and the lack of evidence of initiating obstacles, such as large boulders. However, an analogy could be drawn between these small-scale fluting theories and Moran et al. 's (in press) thrusting/lee deposition mechanism. Both types involve the creation of a low pressure zone in the lee of a rigid basal obstacle, and subsequent lee deposition. Based on the height of large-scale flutings, transport by Shaw and Freschauf's (1973) secondary flow seems more appropriate than the squeezing up of water-saturated debris into subglacial tunnels proposed in most small-scale fluting papers (eg. Boulton, 1976).

Recommendations

Further study is needed in this area on two fronts. More fabric analyses are needed to investigate the possible relationship between consistency of ice flow and landform type. That is, do flutings result from periods of prolonged, consistent ice flow? Further, some method of dating the landforms of the three fluting fields in east-central Alberta, the Lac la Biche, Cold Lake and Athabasca fields, is needed in an attempt to pinpoint the date of final Wisconsin ice retreat from this region, and to establish any relationships which may exist between the three fields. For example, is the Athabasca field contemporaneous with the other two?

An extensive study of the Lac la Biche field, including the area of Cold Lake fluting convergence, and the area in Saskatchewan, would be extremely useful in any study of the glacial history of this area of Alberta. Also, a thorough study of the entire Lac la Biche field might reveal some important information on ice flow characteristics during advance.

It must be kept in mind that the theories proposed by Shaw and Freschauf (1973), and Moran et al. (in press) are largely kinematic ones, although a basal temperature model is presented in the second paper. More intensive glaciological work is necessary in order to examine the characteristics of internal ice movements, and to create a dynamic basis for the kinematic theories presented by geomorphologists.

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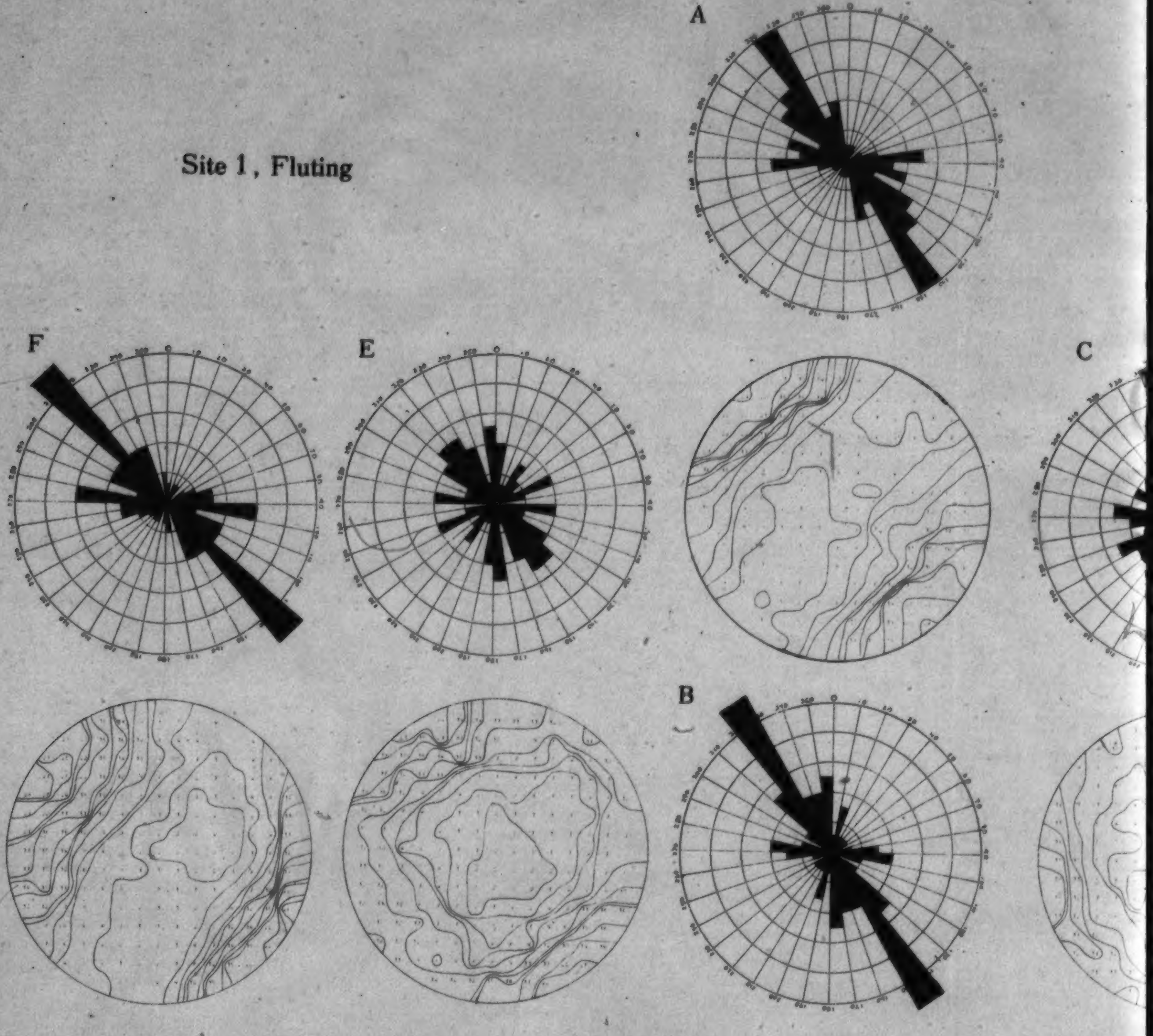
Appendices

Appendix A

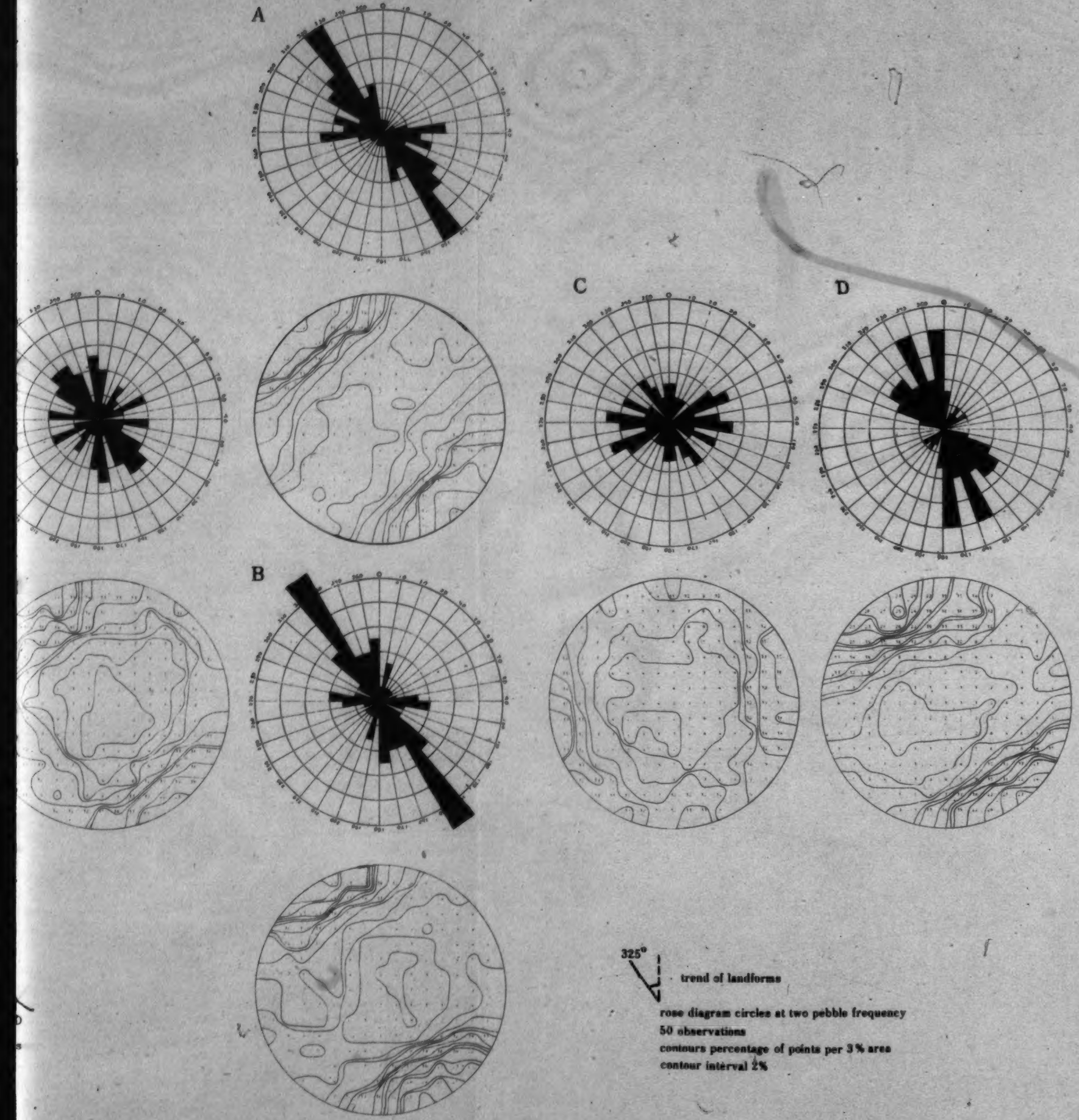
Macrofabric Rose and Contour Diagrams

Site 1, Fluting



location of sample sites

1z

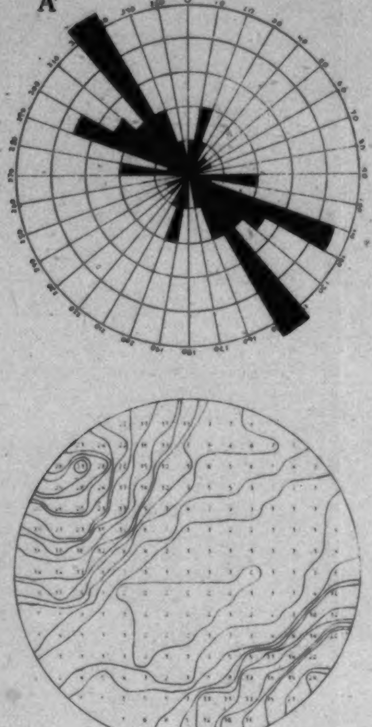


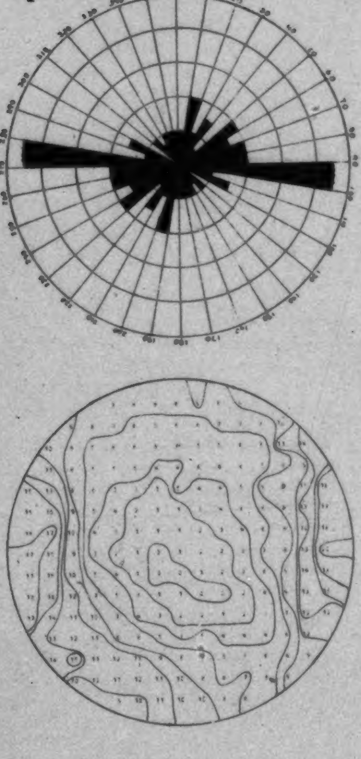
325°
trend of landforms

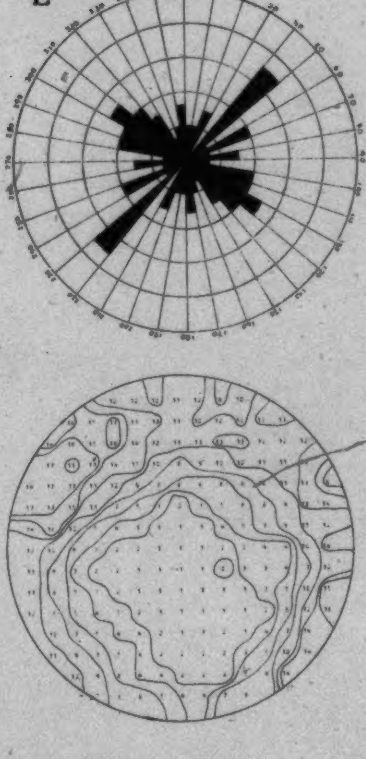
rose diagram circles at two pebble frequency
50 observations
contours percentage of points per 3 % area
contour interval 2%

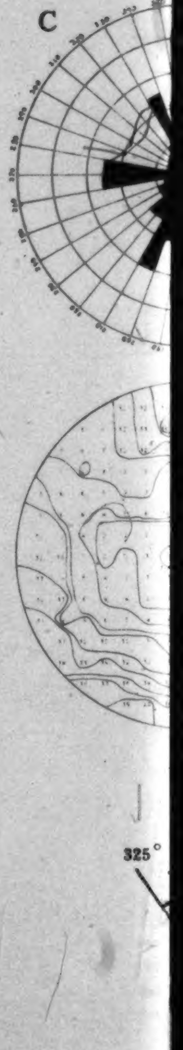
2 of 2

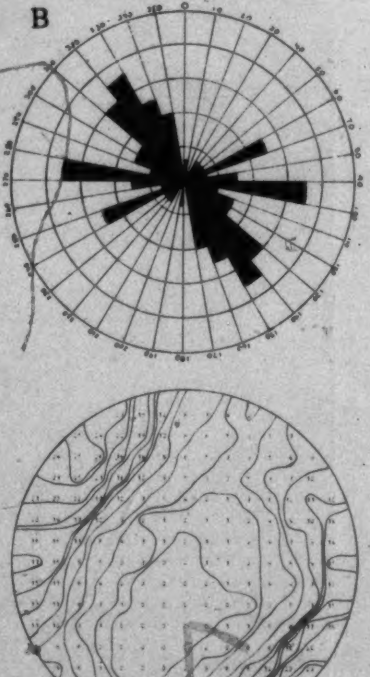
Site 2, Drumlin

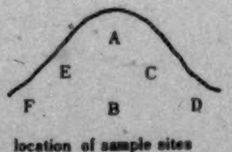




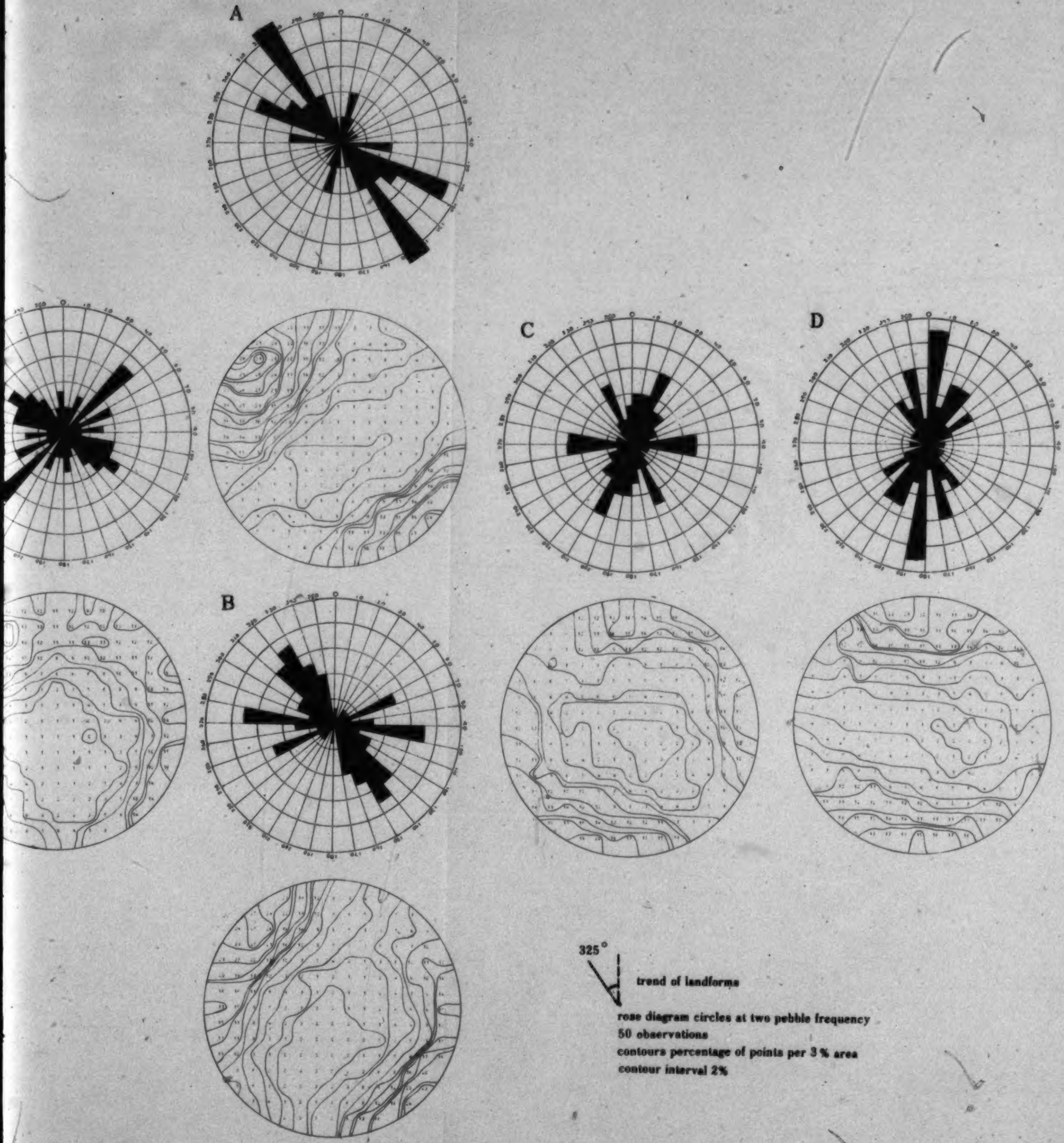








location of sample sites

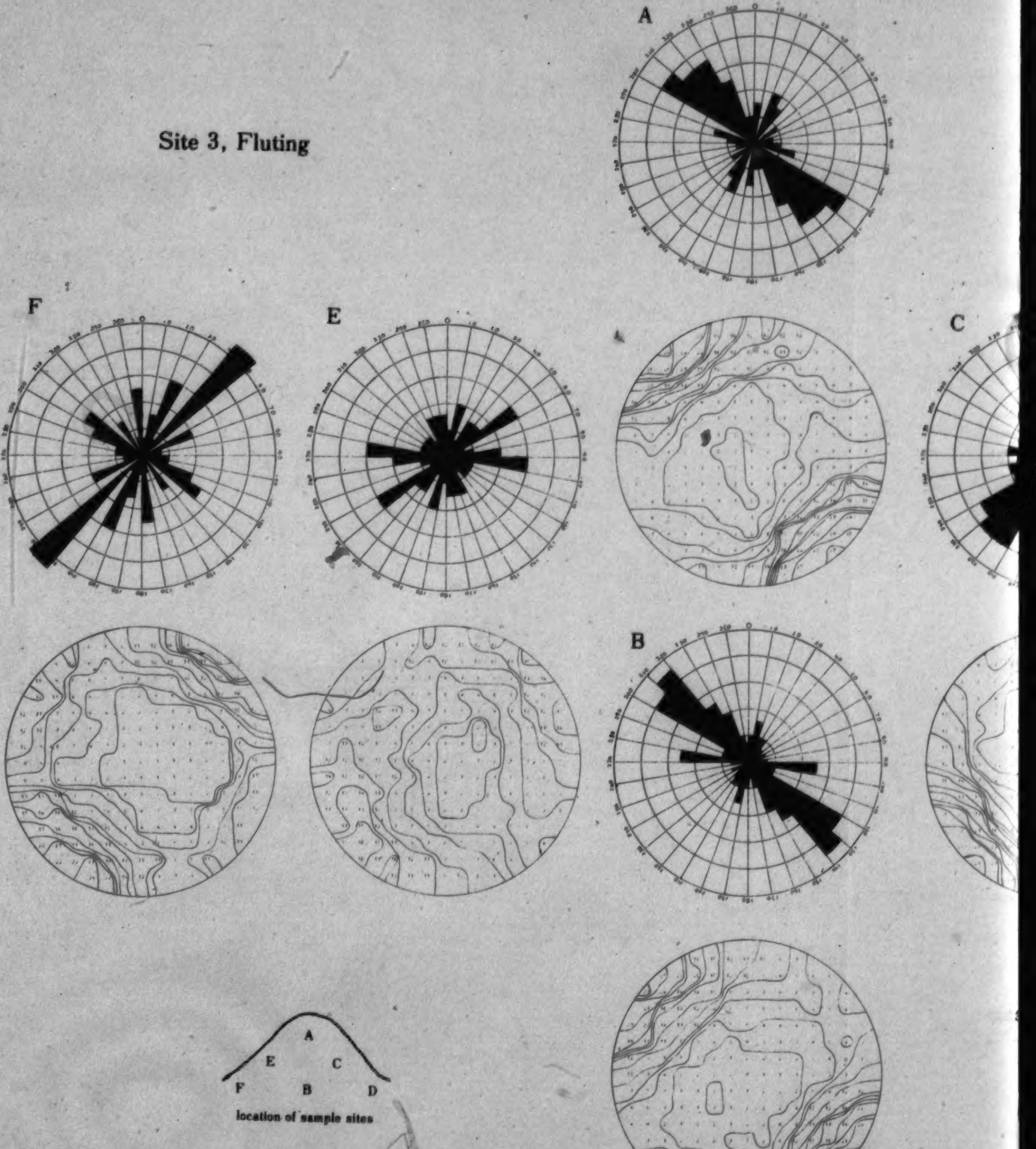


trend of landforms

rose diagram circles at two pebble frequency
50 observations
contours percentage of points per 3 % area
contour interval 2%

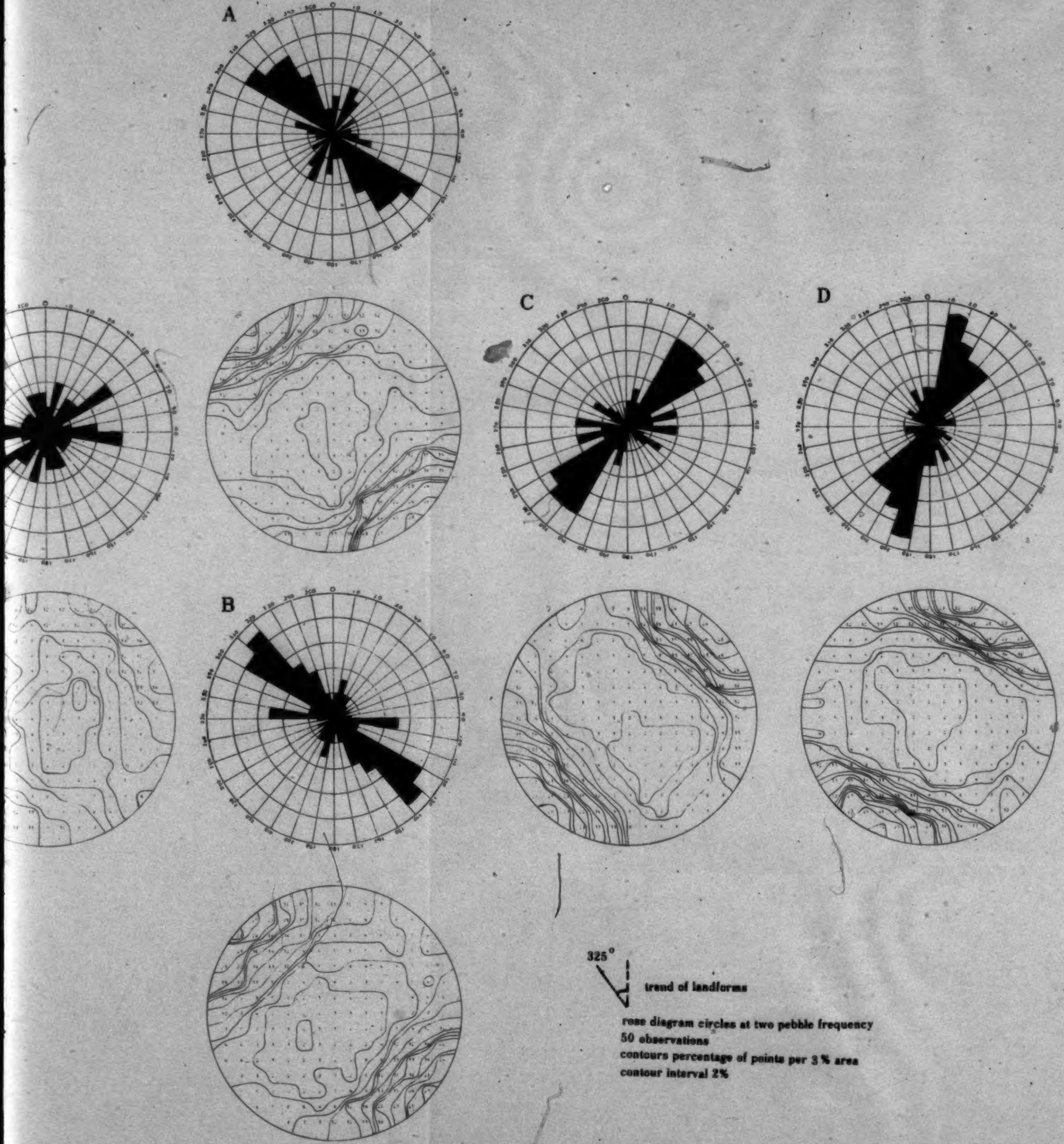
2 of 2

Site 3, Fluting



location of sample sites

1 of



trend of landforms

rose diagram circles at two pebble frequency

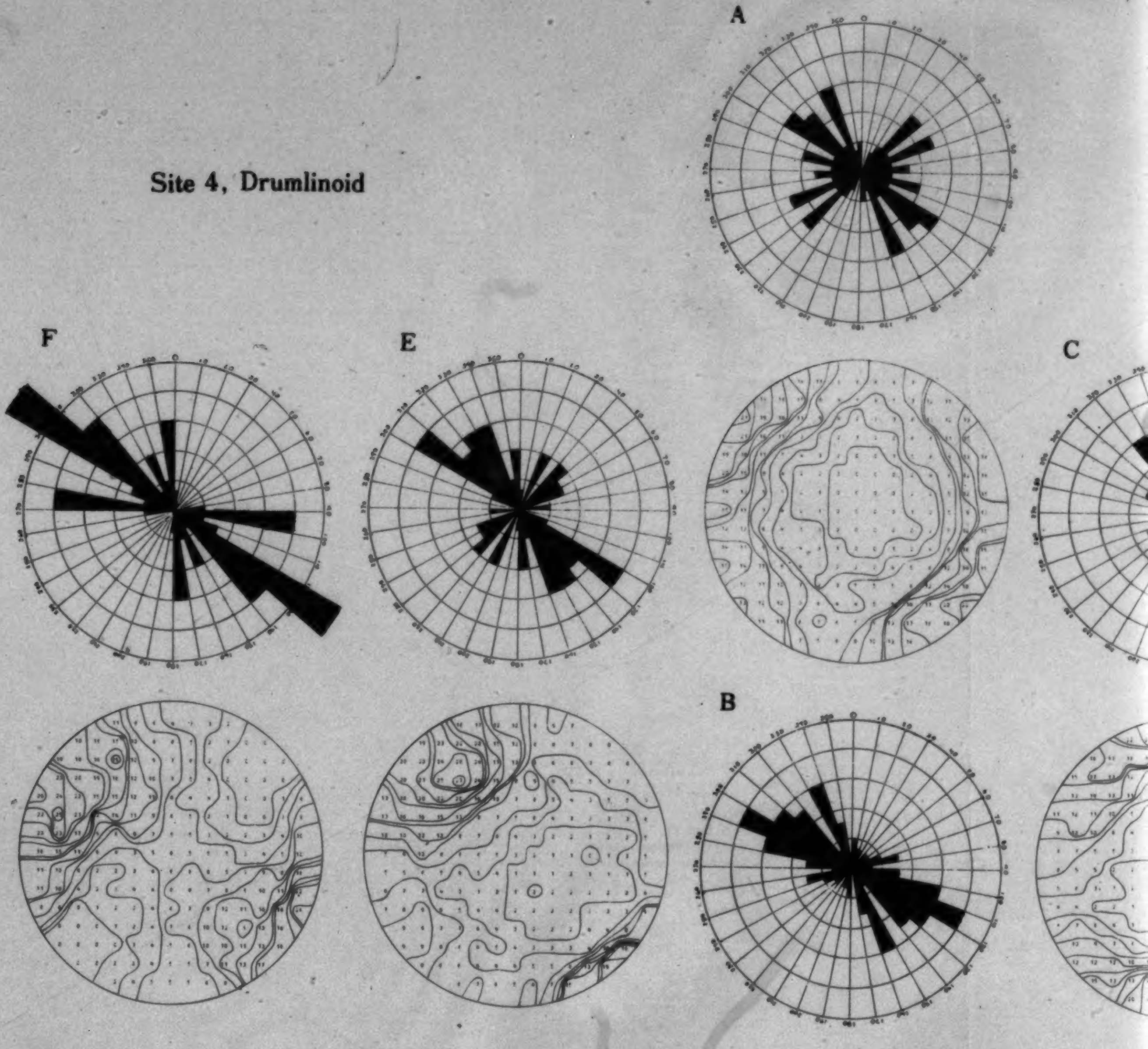
50 observations

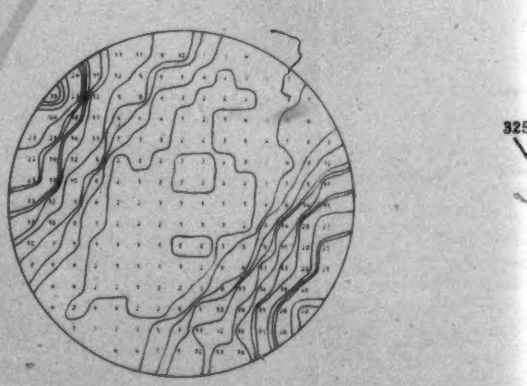
contours percentage of points per 3% area

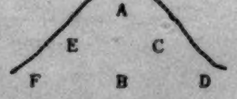
contour interval 2%

2 of 2

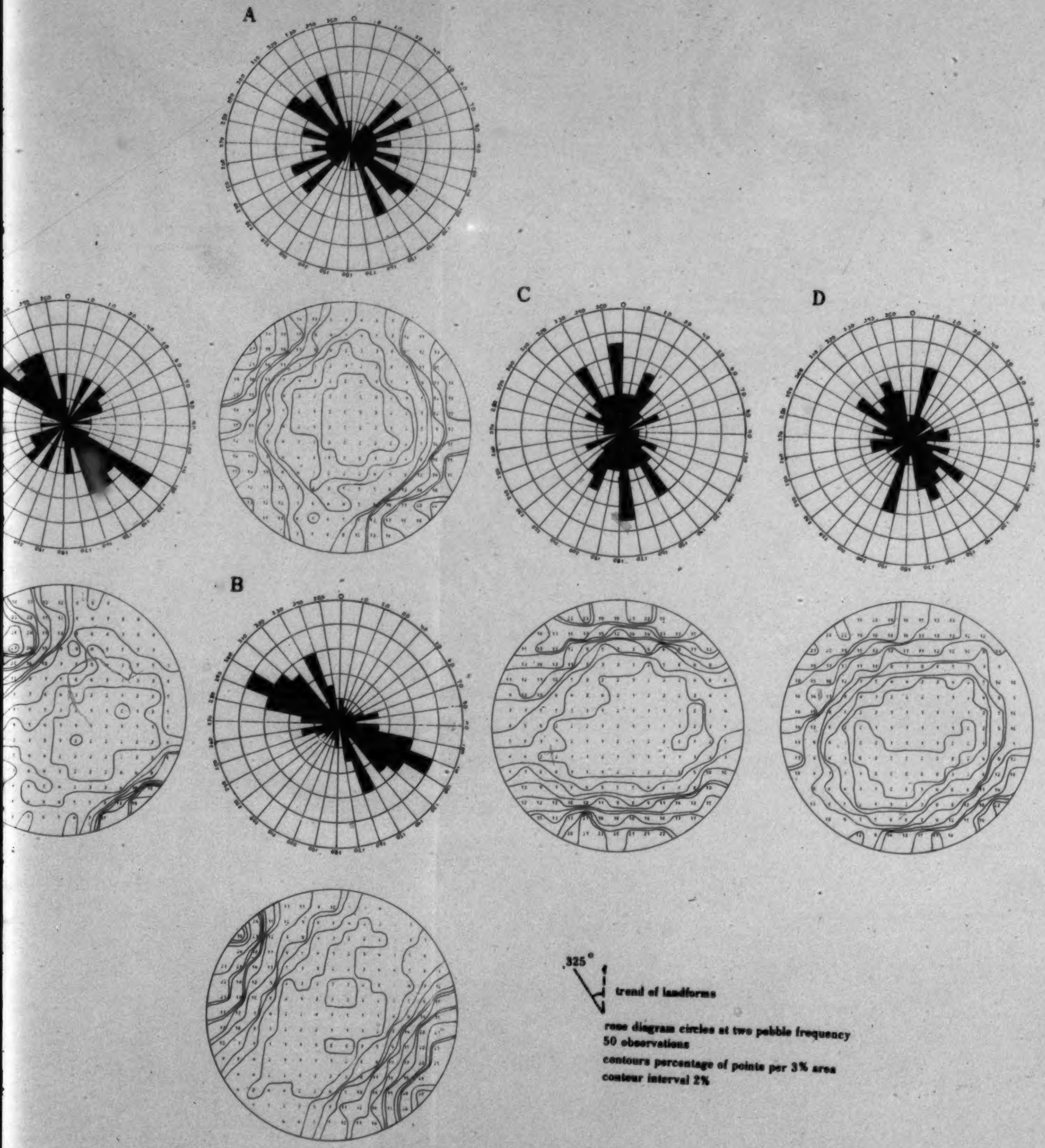
Site 4, Drumlinoid







location of sample sites



trend of landforms

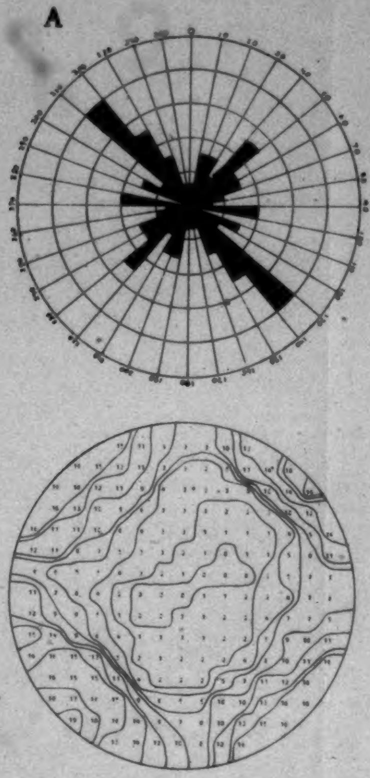
rose diagram circles at two pebble frequency
50 observations

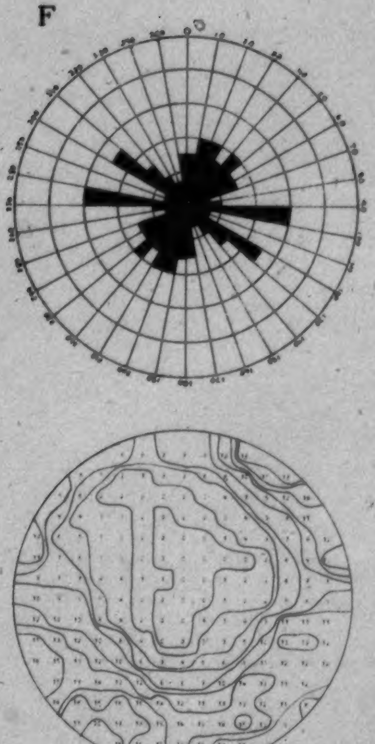
contours percentage of points per 3% area

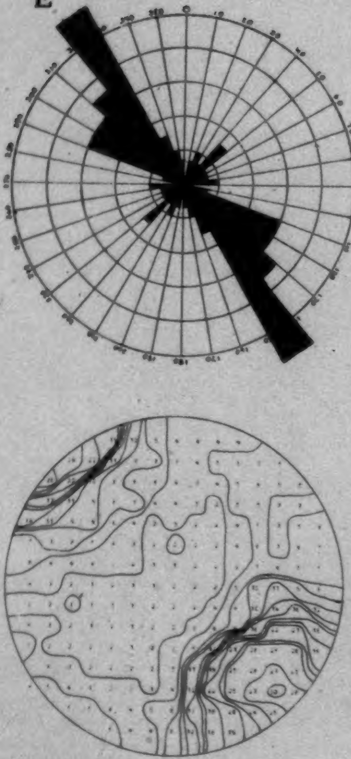
contour interval 2%

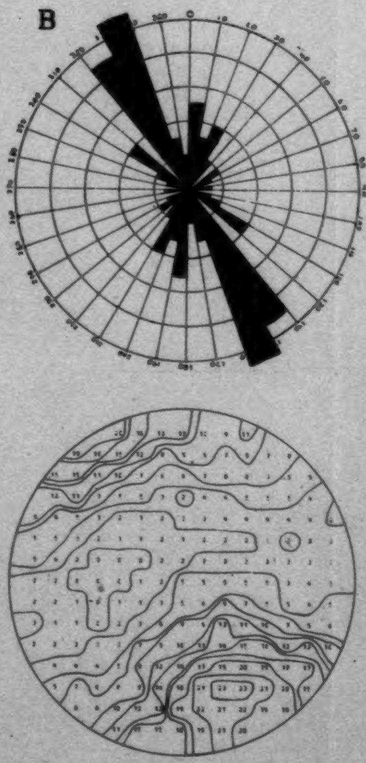
2 of 2

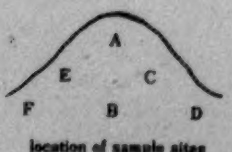
Site 5, Fluting





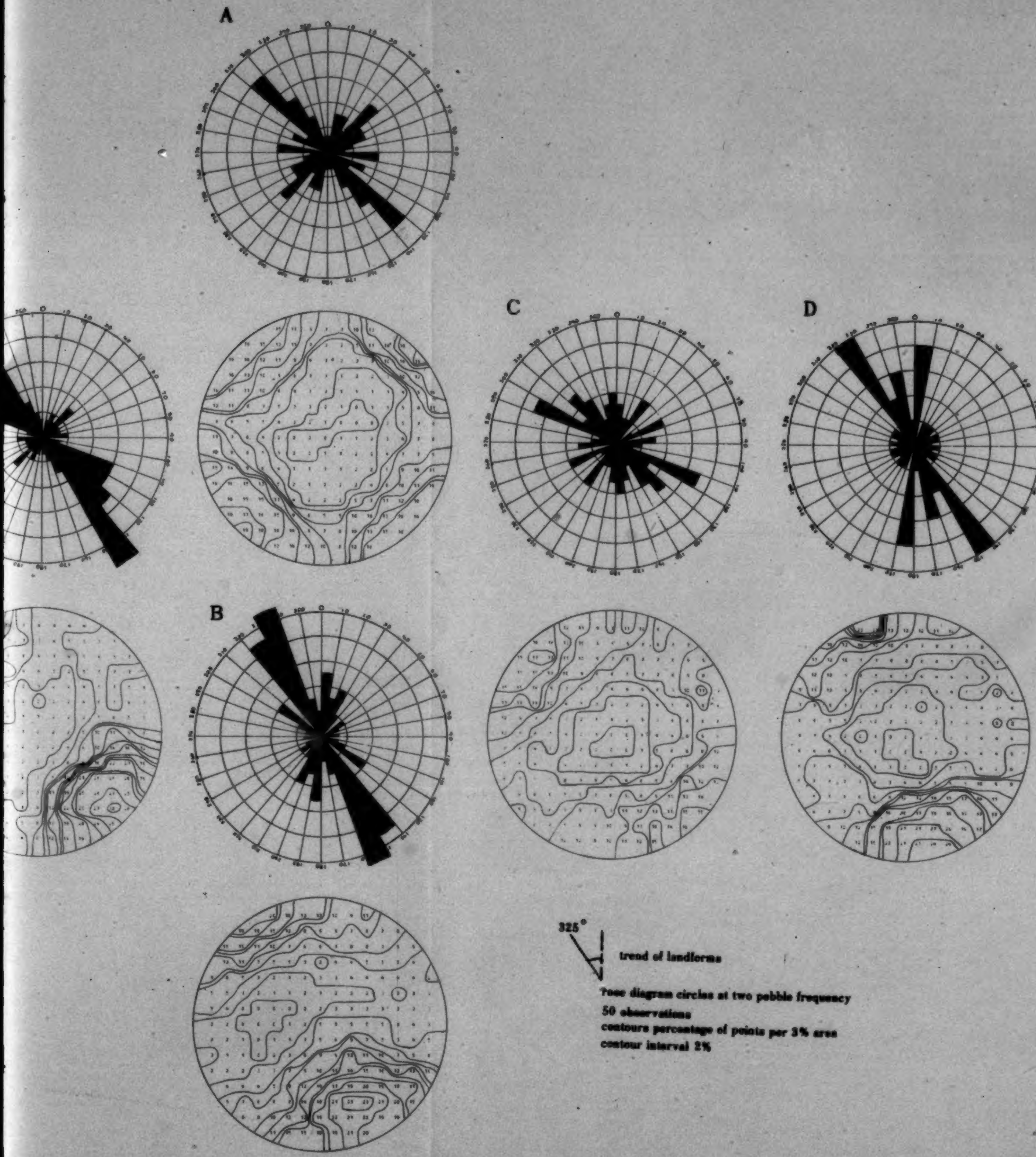






location of sample sites

1f

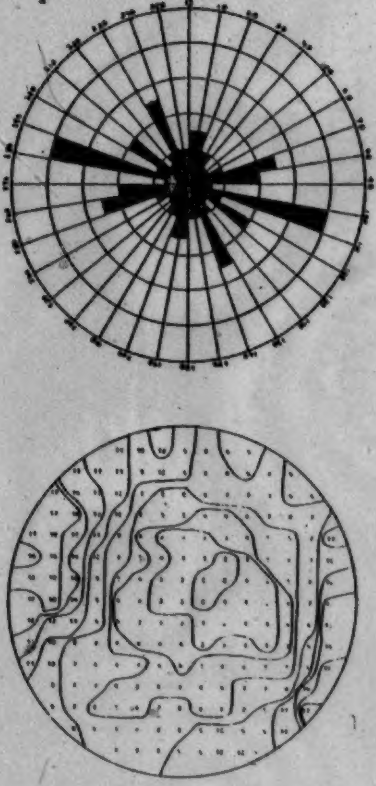


rose diagram circles at two pebble frequency
50 observations
contours percentage of points per 3% area
contour interval 2%

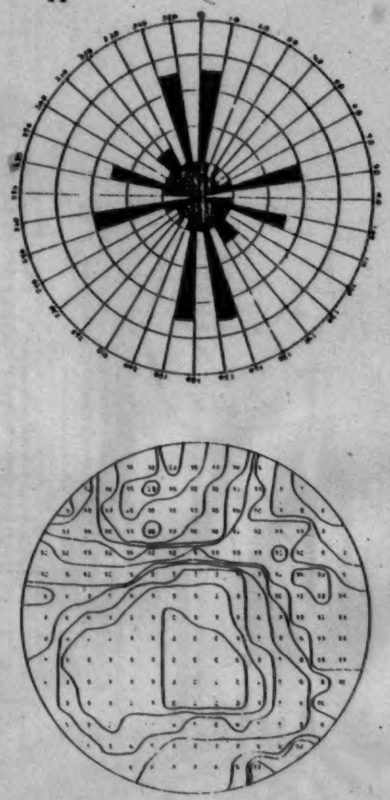
2 of 2

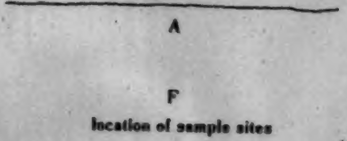
Site 6, Fluting

F



A





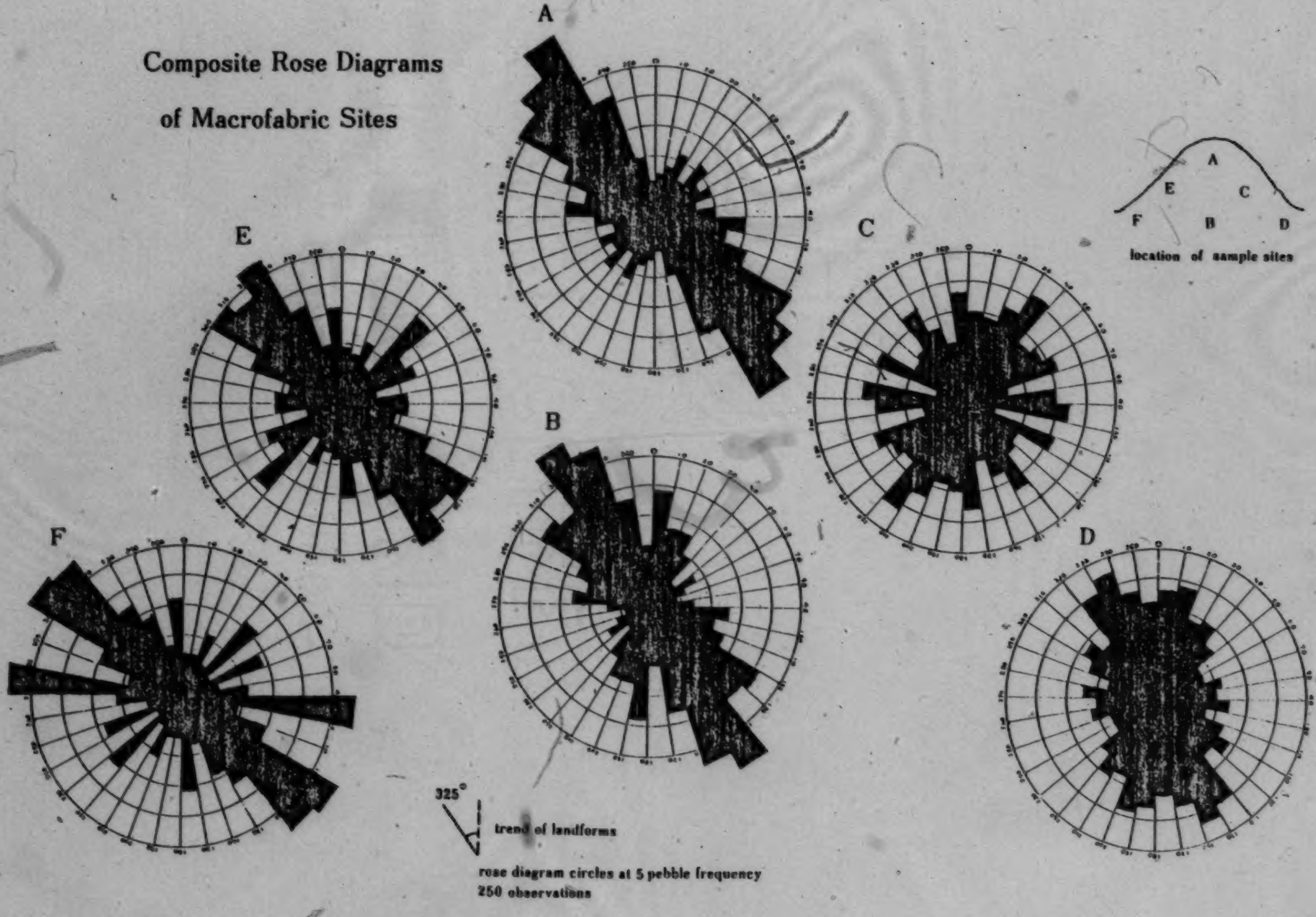
location of sample sites

trend of landforms

rose diagram circles at two pebble frequency
50 observations
contours percentage of points per 3% area
contour interval 2%

Composite Rose Diagrams

of Macrofabric Sites

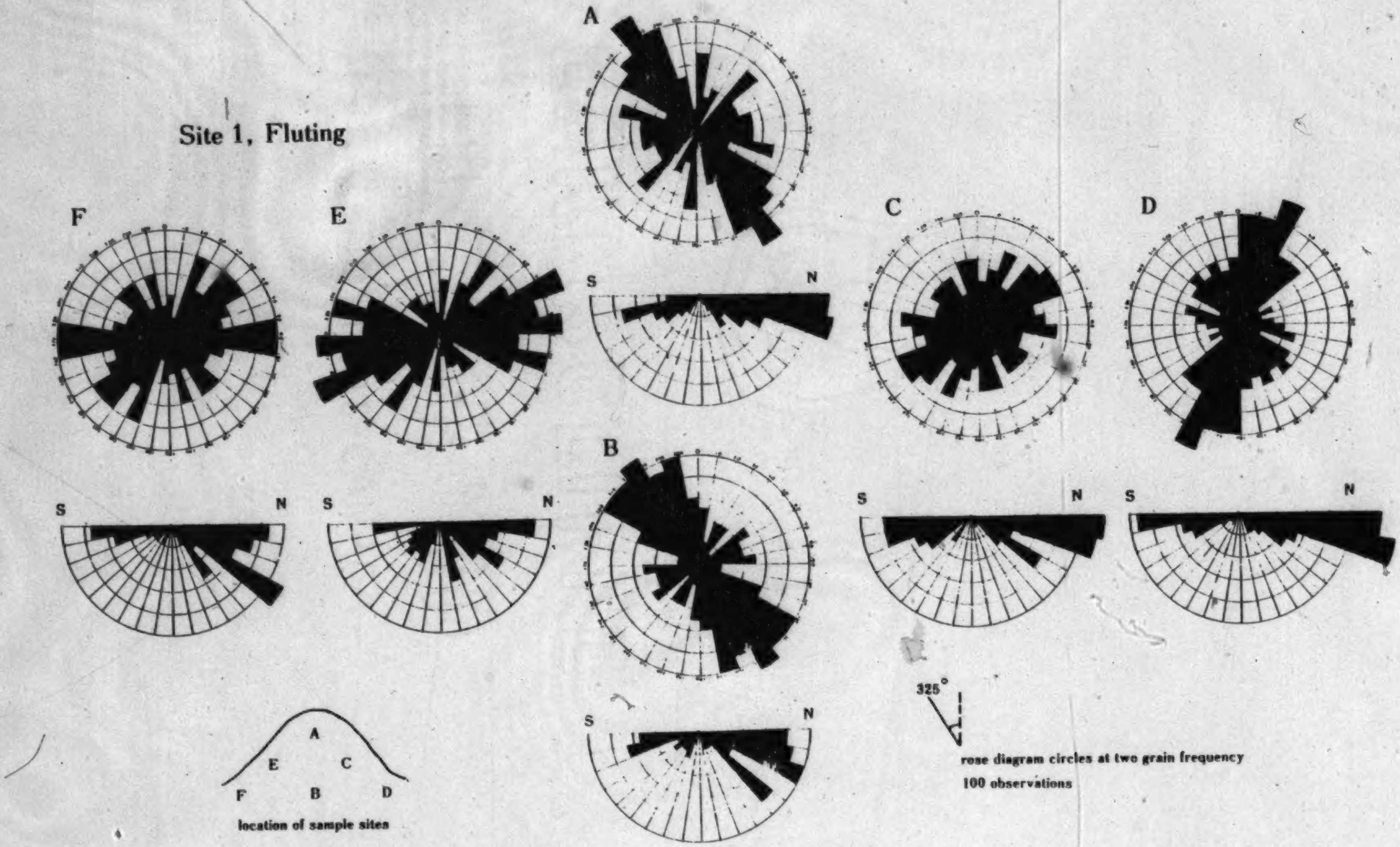


location of sample sites

rose diagram circles at 5 pebble frequency
250 observations

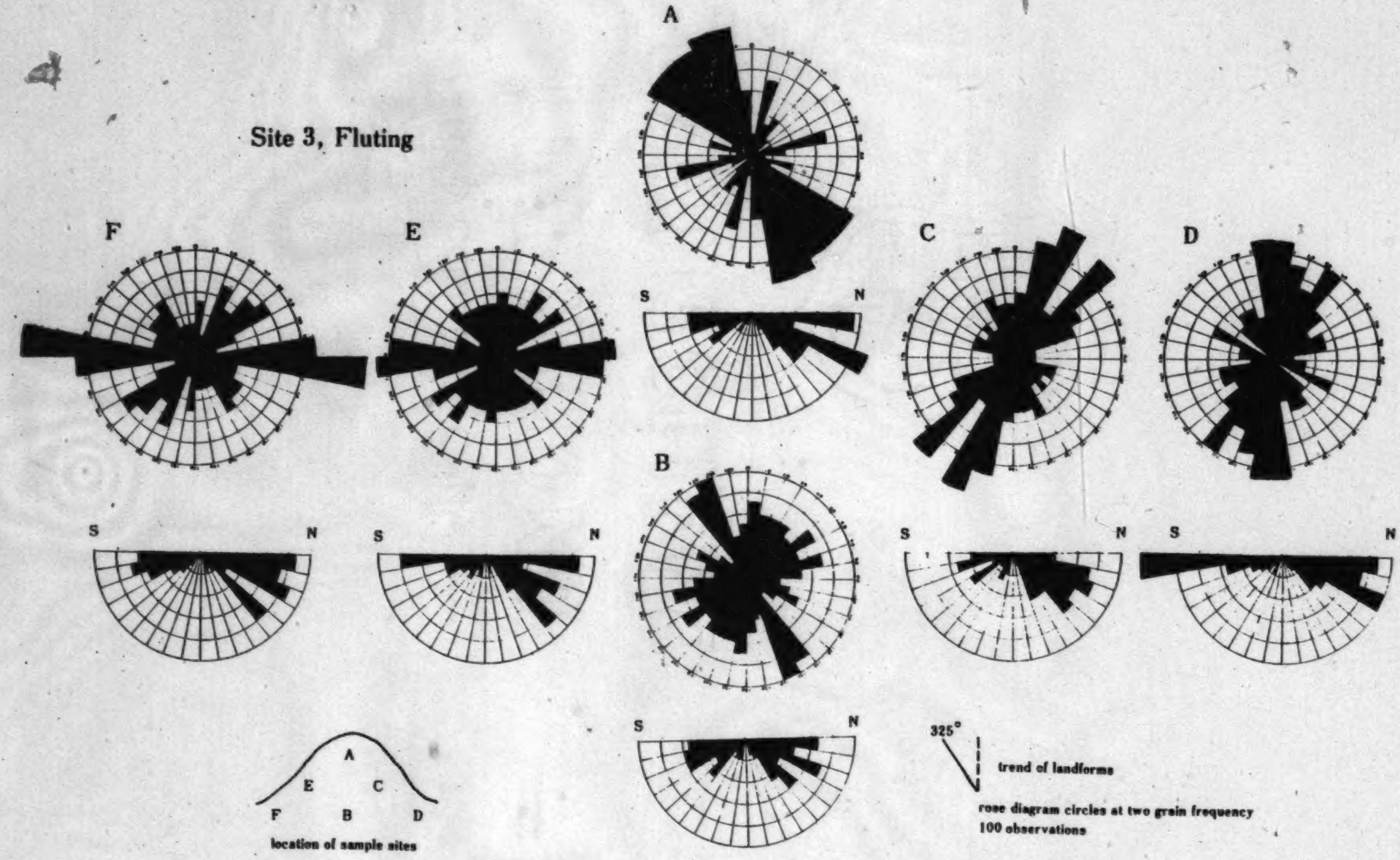
Appendix B

Microfabric Rose and Dip Diagrams



Site 1, Fluting

Site 3, Fluting



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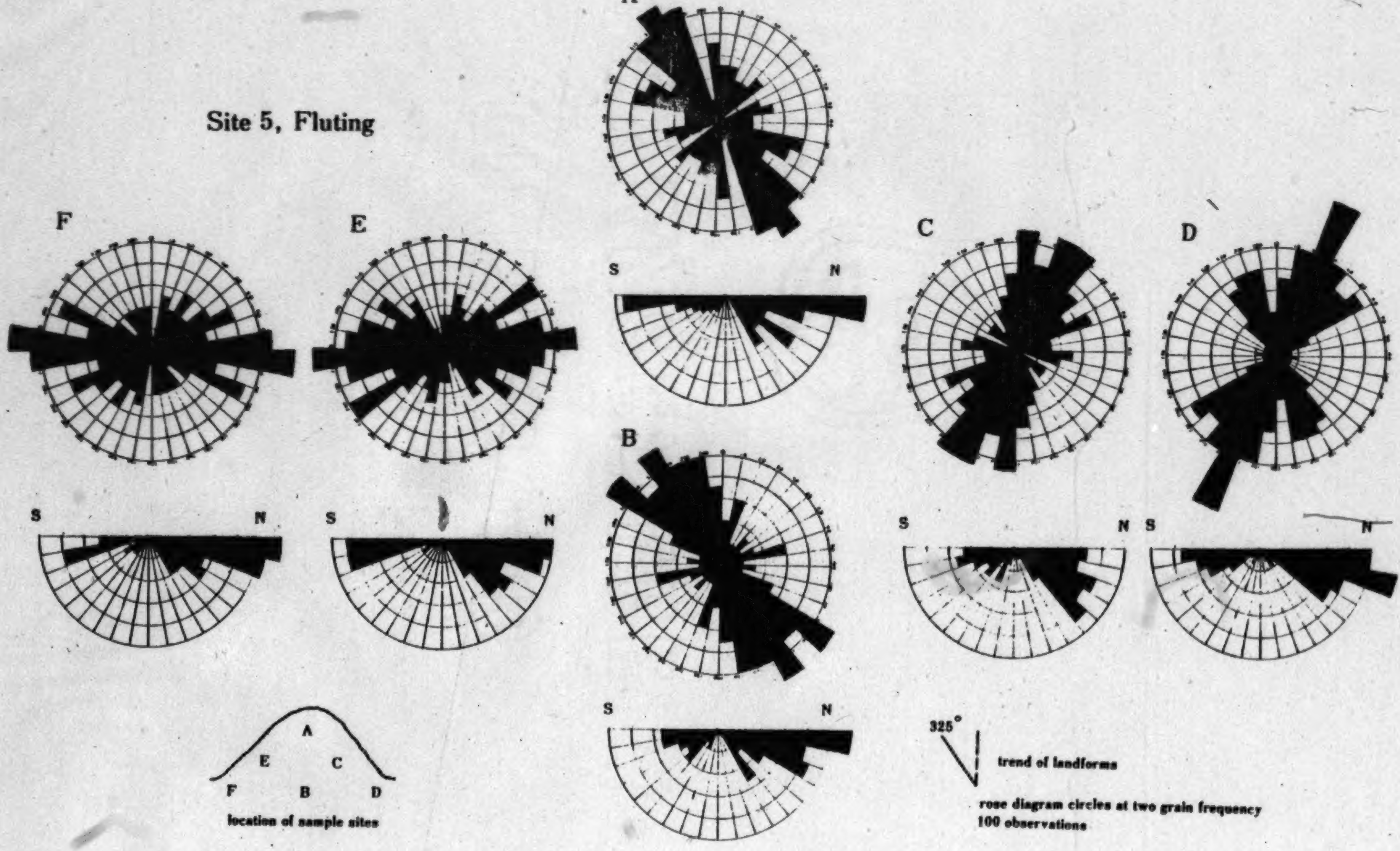


Appendix C

Macrofabric Statistical Data

Macrofabric Statistical Data

Sample #	V_1 Azimuth (°)	V_1 Plunge (°)	S_1	Local Direction of Glacier Flow (°)	Divergence of V_1 from Glacier Flow Direction (°)	V_3 Azimuth (°)	V_3 Plunge (°)	S_3	$\overline{V}$ (°)	R
1A	130	5.9	0.634	325	172	232	63.7	0.155	137	41.8
1B	330	0.5	0.641	325	5	61	71.7	0.126	321	38.5
1C	75	1.7	0.468	325	110	320	85.8	0.176	95	33.3
1D	333	6.3	0.679	325	8	228	67.4	0.096	335	43.2
1E	324	2.9	0.548	325	1	74	81.3	0.097	322	36.3
1F	299	13.2	0.673	325	26	123	76.8	0.110	302	41.0
2A	316	13.3	0.680	325	9	114	75.7	0.110	321	42.8
2B	303	9.3	0.646	325	22	182	72.7	0.085	284	37.4
2C	25	2.9	0.516	325	60	133	80.1	0.143	33	36.6
2D	5	5.9	0.591	325	40	115	73.2	0.162	10	41.3
2E	301	14.2	0.490	325	24	117	65.6	0.106	297	33.7
2F	258	2.3	0.518	325	67	23	86.0	0.150	254	34.1
3A	146	1.9	0.628	325	179	242	74.2	0.107	144	40.0
3B	316	2.0	0.613	325	9	220	71.9	0.129	322	40.5
3C	229	0.4	0.673	325	96	136	81.8	0.083	232	39.4
3D	201	1.5	0.703	325	124	85	86.5	0.065	197	41.8
3E	235	10.2	0.472	325	90	117	69.5	0.194	259	33.2
3F	216	9.0	0.527	325	109	59	80.3	0.124	232	35.1

Macrofabric Statistical Data

	V_1			Local	Divergence of	V_3				
Sample #	Azimuth (°)	Plunge (°)	S_1	Direction of Glacier Flow (°)	V_1 from Glacier Flow Direction (°)	Azimuth (°)	Plunge (°)	S_3	$\overline{V}$ (°)	R
4A	292	1.3	0.551	325	33	37	85.2	0.095	286	36.8
4B	121	2.4	0.653	325	156	309	87.6	0.128	122	41.2
4C	352	1.0	0.605	325	27	87	78.7	0.098	352	38.2
4D	326	11.0	0.561	325	1	161	78.7	0.076	339	35.5
4E	322	26.5	0.586	325	3	118	61.3	0.140	310	35.9
4F	304	11.2	0.614	325	21	35	5.2	0.249	310	44.0
5A	284	5.5	0.459	325	41	54	81.6	0.106	325	30.5
5B	160	18.0	0.626	325	165	272	49.6	0.158	155	40.0
5C	320	1.2	0.496	325	5	195	87.9	0.175	356	32.7
5D	164	8.4	0.584	325	161	40	75.1	0.149	161	38.4
5E	133	15.2	0.650	325	168	252	60.1	0.138	130	40.0
5F	214	15.8	0.508	325	111	352	69.2	0.105	204	30.9
6A	346	24.0	0.538	325	21	206	59.6	0.107	328	34.4
6F	292	12.0	0.498	325	33	86	76.8	0.158	275	33.9

Appendix D

Microfabric Statistical Data

Microfabric Statistical Data

Sample #	Vector Mean (^{o})	Vector Strength	von Mises χ^2 Value	10^{o} Modal Class Midpoint	% Plunge up-ice	% Plunge down-ice	Plunge Proportion Significance Value
1A	131.6	0.18	12.74	145	59	41	1.77
1B	144.7	0.31	9.45	145	63	37	2.51
1C	74.7	0.35	14.21	55	62	38	2.34
1D	9.7	0.31	14.37	15	65	35	2.87
1E	56.3	0.09	8.03	85	60	40	1.96
1F	40.2	0.19	15.31	55	66	34	3.05
3A	149.3	0.38	16.02	145	64	36	2.70
3B	12.7	0.09	14.66	5	54	46	0.81
3C	23.4	0.31	13.41	25	65	35	2.87
3D	14.2	0.29	10.07	15	55	45	1.00
3E	3.7	0.41	25.58	85	60	40	1.96
3F	87.2	0.18	27.19	85	61	39	2.15
5A	142.9	0.20	12.72	145	62	38	2.34
5B	145.8	0.43	17.76	145	62	38	2.34
5C	22.0	0.39	6.55	25	61	39	2.15
5D	17.1	0.51	18.34	25	63	37	2.52
5E	79.6	0.32	16.73	85	67	33	3.22
5F	77.2	0.32	19.52	95	66	34	3.05

Appendix E

Till Textural Data

TILL TEXTURAL DATA

Sample #	Depth (m)	% sand	% silt	% clay
1A	1.0	30.2	27.2	42.6
1B	3.0	28.1	24.6	47.3
1C	3.0	28.3	25.2	46.5
1D	2.0	30.6	25.0	44.4
1E	3.0	33.1	25.9	41.0
1F	2.0	29.1	28.2	42.7
2A	1.5	32.6	23.7	43.7
2B	3.5	24.9	26.5	48.7
2C	3.0	34.0	23.7	42.3
2D	3.5	40.3	21.5	38.2
2E	2.5	28.7	27.2	44.1
2F	2.5	40.3	25.5	34.1
3A	1.0	37.0	24.8	38.2
3B	3.5	40.7	23.4	35.8
3C	3.5	37.5	24.5	38.2
3D	3.0	38.2	26.9	34.9
3E	3.5	35.5	26.4	38.1
3F	3.0	33.7	23.3	43.0
4A	1.0	40.7	29.5	29.9
4B	2.0	37.8	24.5	37.7
4C	2.0	35.2	25.2	39.6
4D	1.5	43.9	25.3	30.8
4E	2.0	34.8	25.6	39.6
5A	1.0	30.0	23.6	46.4
5B	2.5	33.6	26.8	39.6
5C	2.5	33.9	24.6	41.5
5D	2.0	34.7	27.1	38.1
5E	2.5	31.2	25.7	43.0
5F	2.0	31.6	23.9	44.5
6A	1.0	36.5	18.5	45.0
6F	2.5	31.6	26.8	41.6

Continued ...

Sample #	Depth (m)	% sand	% silt	% clay
7	1.0	36.4	26.7	36.9
8	2.5	31.7	30.2	38.0
8	3.5	35.8	27.7	36.5
8	6.0	27.3	25.2	47.5
9	1.0	31.2	26.5	42.3
9	1.5	35.2	20.0	44.8
10	1.0	6.8	40.1	53.1
10	2.0	22.5	40.7	36.8
11	0.5	60.1	21.4	18.5
12	1.0	25.9	46.8	27.2
13	2.0	40.2	23.5	36.3
13	2.0	59.7	20.9	19.4
14	1.0	37.6	26.9	35.4
14	2.5	36.3	28.0	35.7
15	1.0	37.9	21.3	40.7
16	1.0	40.0	24.8	35.2
17	2.0	19.2	34.8	46.0
18	2.0	19.3	29.0	51.7
18	2.5	10.6	46.0	43.4
18	3.0	69.4	12.2	18.4
19	2.0	45.1	22.4	32.5
20	1.0	35.0	41.0	24.0
21	0.5	41.5	25.6	32.8
21	3.0	21.9	23.8	44.3
21	3.2	20.6	58.1	21.3
21	3.4	25.9	31.0	43.0
22	0.5	41.2	31.7	27.0
22	1.0	35.8	29.1	35.1
22	7.0	5.5	63.2	31.3
22	7.8	32.1	30.8	37.1
23	0.5	62.7	19.0	18.3
D-1 (R)	1.0	30.5	24.3	24.3
D-1 (R)	4.0	31.9	27.9	40.2
D-1 (R)	9.0	31.7	23.9	44.4
D-1 (R)	18.0	28.8	24.6	46.6
D-1 (R)	20.0	33.9	27.8	38.4
D-2 (R)	1.0	38.1	27.7	34.2
D-2 (R)	2.0	29.9	29.4	40.7
D-2 (R)	10.0	34.5	26.2	39.3
D-2 (R)	15.0	52.1	26.9	21.0
D-2 (R)	16.0	34.8	34.3	30.8
D-3 (T)	1.0	32.0	23.2	44.8
D-3 (T)	6.0	32.5	25.1	42.4
D-3 (T)	11.0	39.5	24.9	35.6

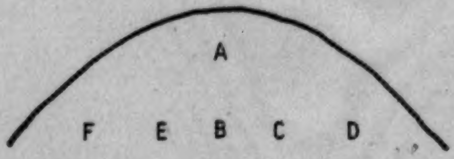
Continued ...

Sample #	Depth (m)	% sand	% silt	% clay
D-3 (T)	19.0	39.4	27.3	33.4
D-4 (R)	1.0	28.9	25.8	45.3
D-4 (R)	5.0	30.9	22.4	46.7
D-4 (R)	10.0	30.9	28.1	40.9
D-4 (R)	12.0	33.2	24.3	42.5
D-4 (R)	17.0	39.6	27.8	32.7
D-5 (R)	1.0	32.6	29.0	38.4
D-5 (R)	8.0	35.0	29.2	35.8
D-5 (R)	15.0	38.8	27.0	34.2
D-6 (T)	1.0	34.8	24.2	41.0
D-6 (T)	4.0	37.2	29.3	33.5
D-6 (T)	7.0	33.8	28.2	38.0
D-6 (T)	14.0	38.8	26.5	34.7
D-7 (R)	1.0	43.7	24.0	32.3
D-7 (R)	5.0	35.9	29.7	34.4
D-7 (R)	7.0	31.7	30.4	37.9
D-7 (R)	15.0	33.9	27.2	38.9
D-7 (R)	21.0	44.2	26.1	29.7
D-8 (T)	1.0	53.2	24.6	22.2
D-8 (T)	2.6	35.9	25.5	38.6
D-8 (T)	6.0	32.8	29.1	38.1
D-8 (T)	11.0	34.7	28.7	36.6
D-8 (T)	14.0	36.7	24.7	38.6

Prefix 'D' designates drill hole sample

Suffix 'R' indicates hole drilled on fluting ridge

Suffix 'T' indicates hole drilled in fluting trough



Fabric Sampling Scheme

Appendix F

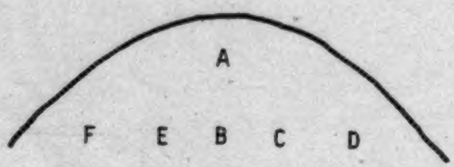
Sand Grain Lithology

SAND GRAIN LITHOLOGY

Sample #	Depth (m)	% Crystalline	% Carbonate	% Local Clastics
1A	1.0	92.1	6.3	1.6
1B	3.0	90.8	5.6	3.7
1C	3.0	89.0	6.0	5.0
1D	2.0	92.3	6.9	0.8
1E	3.0	86.1	7.7	6.3
1F	2.0	93.0	3.5	3.5
2A	1.5	93.1	5.2	1.7
2B	3.5	92.4	2.9	4.8
2C	3.0	94.5	5.0	0.6
2D	3.5	95.8	2.6	1.5
2E	2.5	89.6	7.2	3.2
2F	2.5	95.7	3.4	0.9
3A	1.0	93.5	5.3	1.2
3B	3.5	93.7	4.0	2.3
3C	3.5	91.2	5.5	3.4
3D	3.0	89.2	6.0	4.8
3E	3.5	90.9	4.6	4.6
3F	3.0	94.1	4.7	1.2
4A	1.0	82.7	3.6	12.1
4B	2.0	91.2	7.7	1.2
4C	2.0	95.0	4.3	0.7
4D	1.5	92.6	3.5	4.0
4E	2.0	92.3	5.4	2.4
5A	1.0	93.3	4.8	2.0
5B	2.5	95.3	3.0	1.8
5C	2.5	91.5	6.5	2.0
5D	2.0	89.4	8.4	2.1
5E	2.5	92.2	5.6	1.4
5F	2.0	94.7	4.4	0.9
6A	1.0	98.2	0.0	1.7
6F	2.5	92.5	6.6	0.8

Continued ...

Sample #	Depth (m)	% Crystalline	% Carbonate	% Local Clastics
7	1.0	93.1	5.3	1.6
8	2.5	95.4	2.8	1.9
8	3.5	95.6	3.0	1.5
8	6.0	85.5	7.6	7.0
9	1.0	94.9	4.2	0.9
9	1.5	98.6	0.5	0.9
11	1.5	92.5	7.1	0.5
12	1.0	85.0	11.5	3.5
13A	2.0	97.2	1.4	1.4
13B	2.0	93.8	4.9	1.3
14	1.0	93.3	4.1	2.6
14	2.5	94.8	4.3	1.1
15	1.0	99.4	0.0	0.6
16	1.0	93.2	6.3	0.6
17	2.0	90.2	8.0	2.0
18	2.0	93.3	4.4	2.2
19	2.0	97.9	1.6	0.5
21	0.5	97.5	0.0	2.5
21	3.0	91.4	5.2	3.4
21	3.4	97.4	0.9	1.8
22	1.0	92.9	5.1	2.1
22	7.8	95.6	1.9	2.5



Fabric Sampling Scheme

Appendix G

Macrofabric Data

Macrofabric Data

Sample #	Orientation	Dip	Sample #	Orientation	Dip
1A	146	43	1B	70	24
	130	49		20	16
	109	43		327	24
	168	1		90	39
	83	3		150	10
	53	58		326	49
	265	69		134	5
	153	1		192	15
	133	7		173	16
	179	6		2	33
	270	13		176	4
	277	14		195	4
	122	3		352	15
	158	2		156	14
	160	5		345	4
	110	45		149	11
	100	26		277	53
	255	24		210	58
	121	21		221	22
	316	2		17	15
	321	22		55	17
	25	42		173	26
	287	30		277	39
	65	14		272	37
	131	9		328	22
	120	14		146	6
	317	22		135	25
	87	12		260	6
	336	33		285	45
	87	30		154	9
	328	9		153	16
	321	14		134	11
	270	2		311	12
	127	38		265	36
	140	0		328	7
	307	13		120	10
	141	7		177	19
	70	68		142	22
	325	8		144	15
	134	3		137	10
	327	29		82	6
	162	4		167	2
	80	0		323	8
	13	1		308	7
	188	38		145	9
	297	10		345	20
	108	14		283	30
	143	27		322	2
	147	2		340	4
	166	31		146	3

Sample #	Orientation	Dip	Sample #	Orientation	Dip
1C	97	17	1D	322	22
	249	21		295	5
	83	2		280	7
	32	11		163	33
	55	0		305	11
	124	4		348	8
	294	42		125	8
	51	10		168	17
	187	27		115	30
	243	11		350	5
	163	66		327	12
	182	22		316	9
	116	47		180	3
	92	1		335	4
	83	15		34	6
	17	23		315	0
	96	3		130	24
	90	63		150	25
	351	34		116	31
	202	27		300	21
	324	53		327	7
	66	12		358	20
	235	12		10	66
	195	1		335	6
	299	10		350	6
	357	7		355	28
	172	25		345	4
	126	18		305	11
	77	15		155	7
	72	10		135	12
	234	18		315	24
	326	56		35	22
	328	41		335	12
	28	7		355	22
	87	9		280	14
	242	32		5	12
	155	37		154	4
	145	16		355	35
	156	6		232	12
	278	28		29	7
	295	3		54	34
	218	11		116	28
	5	68		43	27
	280	10		353	35
	68	48		146	2
	180	12		307	11
	336	7		145	11
	107	16		358	28
	347	4		188	29
	81	12		335	42

Sample #	Orientation	Dip	Sample #	Orientation	Dip
1E	227	25	1F	189	53
	297	13		294	19
	6	13		322	11
	285	51		271	38
	309	8		312	14
	243	15		325	17
	248	1		132	25
	226	19		318	36
	219	14		316	6
	145	12		137	13
	153	27		318	6
	354	36		326	31
	315	25		265	10
	256	26		200	11
	312	11		250	53
	215	3		67	8
	54	43		137	4
	198	7		117	7
	97	9		296	13
	351	24		280	28
	323	17		338	12
	1	14		35	17
	282	34		351	39
	354	31		335	53
	123	19		336	34
	148	17		75	7
	151	14		277	20
	93	0		333	31
	274	4		101	12
	336	5		137	6
	250	8		126	2
	338	5		315	31
	246	32		249	22
	359	8		143	3
	323	8		121	5
	241	1		356	17
	317	7		276	18
	318	1		234	2
	118	16		121	16
	173	28		312	18
	212	16		298	57
	131	1		271	8
	181	23		262	11
	205	19		131	16
	122	25		307	4
	95	13		310	15
	129	13		264	2
	321	8		274	17
	342	7		255	10
	2	15		271	14

Sample #	Orientation	Dip	Sample #	Orientation	Dip
2A	158	10	2B	65	16
	153	12		348	31
	285	24		89	7
	115	3		72	33
	303	46		294	5
	305	20		274	16
	246	23		311	9
	293	26		314	14
	274	14		275	12
	45	34		260	12
	316	1		331	30
	168	26		325	9
	322	14		309	12
	340	31		277	38
	321	37		65	7
	319	19		156	8
	334	21		145	11
	275	2		141	5
	290	11		330	13
	321	38		123	6
	147	20		306	11
	143	8		279	17
	158	4		108	2
	298	23		287	43
	296	10		94	24
	13	35		337	17
	17	3		320	4
	194	2		56	53
	274	7		98	18
	140	24		341	2
	149	1		36	17
	194	5		315	47
	292	24		65	5
	3	66		345	18
	305	5		293	13
	314	17		147	25
	327	4		278	27
	148	9		314	23
	21	13		245	16
	320	23		1	30
	1	24		47	8
	275	15		80	2
	326	39		311	14
	290	30		340	27
	301	37		139	2
	291	27		147	6
	203	0		322	27
	136	7		157	16
	118	32		245	4
	307	3		298	8

Sample #	Orientation	Dip	Sample #	Orientation	Dip
2C	185	3	2D	315	8
	359	12		0	14
	352	44		342	40
	88	9		228	13
	38	5		323	18
	87	4		17	18
	346	3		67	3
	192	31		4	30
	277	13		31	52
	292	44		211	64
	348	55		220	42
	149	24		181	51
	228	8		86	8
	202	18		209	21
	4	11		202	8
	339	14		359	9
	204	26		336	9
	220	47		163	2
	10	2		182	6
	189	10		122	16
	206	4		337	3
	95	24		192	24
	238	24		235	1
	30	8		236	20
	51	40		0	24
	354	3		184	8
	66	17		159	20
	334	4		142	10
	333	40		169	15
	23	15		355	55
	97	25		0	19
	42	30		346	22
	209	15		0	16
	274	37		183	29
	81	2		15	10
	193	24		271	4
	267	12		210	18
	328	38		320	12
	288	4		215	44
	336	22		57	32
	6	53		141	16
	82	2		39	22
	70	1		28	40
	278	2		299	39
	62	18		50	35
	335	36		27	3
	193	15		240	7
	138	26		21	1
	25	20		344	36
	218	30		340	32

Sample #	Orientation	Dip	Sample #	Orientation	Dip
2E	305	22	2F	87	25
	309	35		197	42
	339	15		56	64
	135	15		85	30
	290	7		84	24
	46	53		68	25
	308	16		256	10
	291	10		270	8
	286	12		167	11
	202	17		324	11
	23	3		295	5
	315	0		201	8
	314	3		340	13
	86	4		197	27
	257	3		30	37
	69	38		312	30
	240	3		273	33
	267	2		274	6
	17	17		115	25
	27	17		200	7
	355	14		18	18
	1	27		93	7
	65	12		240	29
	198	58		183	10
	223	19		256	15
	44	9		278	4
	105	4		230	19
	340	22		177	33
	231	7		252	6
	316	21		276	1
	355	36		159	17
	0	30		315	26
	48	20		221	23
	224	39		240	2
	292	35		215	19
	326	34		285	13
	102	26		32	40
	105	3		254	11
	305	5		274	2
	278	10		152	20
	226	22		82	48
	80	40		245	27
	358	41		355	33
	62	21		95	14
	301	49		118	7
	293	13		2	27
	165	4		107	4
	46	39		274	47
	322	27		194	17
	45	31		57	10

Sample #	Orientation	Dip	Sample #	Orientation	Dip
3A	304	4	3B	64	14
	0	14		270	12
	102	36		145	5
	327	25		133	23
	74	29		196	24
	96	48		15	39
	3	43		129	26
	325	11		310	19
	101	63		359	30
	138	10		0	2
	122	39		131	17
	347	16		305	3
	300	21		147	47
	338	12		314	56
	144	2		138	69
	237	39		301	19
	137	13		103	6
	320	17		144	11
	121	16		153	10
	136	23		122	11
	145	21		337	5
	340	15		107	11
	136	13		317	34
	321	12		128	9
	142	4		299	16
	32	9		90	1
	152	7		125	14
	213	5		318	14
	289	7		292	21
	207	3		321	19
	82	21		129	1
	137	11		154	12
	272	10		41	45
	23	24		36	27
	305	12		26	10
	302	6		92	25
	316	5		263	12
	207	9		329	25
	157	5		19	11
	127	24		337	1
	231	2		349	1
	24	15		278	40
	173	16		314	2
	155	13		205	21
	154	9		340	5
	33	22		1	47
	359	6		318	8
	133	2		31	5
	181	25		92	19
	302	35		123	17

Sample #	Orientation	Dip	Sample #	Orientation	Dip
3C	240	7	3D	203	5
	194	8		198	20
	84	14		42	12
	264	7		25	14
	90	5		34	3
	217	3		181	11
	236	1		157	4
	296	3		10	5
	43	18		222	11
	38	5		45	4
	94	2		38	2
	36	12		217	6
	47	5		192	15
	308	13		253	25
	232	27		38	4
	223	3		333	5
	230	34		143	9
	255	4		211	11
	143	1		358	7
	45	10		350	2
	49	20		63	29
	199	4		308	4
	357	12		11	25
	20	18		20	7
	46	53		205	8
	69	10		205	4
	214	26		26	4
	30	6		88	3
	230	14		133	43
	41	26		150	7
	92	3		297	10
	237	18		5	10
	278	51		341	21
	233	4		52	4
	138	8		48	9
	8	2		355	32
	225	12		196	16
	238	3		26	8
	214	13		261	38
	315	31		194	18
	309	14		32	7
	4	4		306	3
	215	35		253	12
	253	3		228	34
	14	45		200	18
	76	13		223	6
	129	8		184	6
	258	28		18	9
	24	1		17	2
	35	20		160	20

Sample #	Orientation	Dip	Sample #	Orientation	Dip
3E	259	14	3F	329	47
	104	23		191	44
	345	44		64	62
	235	9		22	9
	87	26		216	23
	308	72		303	26
	237	28		222	24
	314	30		208	18
	277	35		228	12
	236	17		178	8
	177	15		352	7
	80	20		227	1
	170	68		120	7
	43	7		304	14
	146	7		294	12
	212	3		25	16
	200	23		129	11
	261	37		220	12
	56	11		295	7
	194	8		205	33
	24	8		117	6
	272	55		122	10
	19	25		195	1
	347	18		187	41
	3	38		227	13
	72	2		114	26
	271	30		25	12
	158	17		276	2
	344	36		222	2
	359	4		42	12
	129	39		221	1
	111	6		355	4
	216	17		104	1
	290	25		243	3
	82	34		220	29
	231	6		149	19
	47	23		280	46
	336	47		228	23
	337	31		148	37
	195	17		19	14
	246	4		240	1
	91	22		200	16
	214	42		48	16
	55	25		275	31
	273	38		341	28
	226	42		251	3
	285	54		354	7
	180	5		248	61
	277	20		177	4
	133	25		82	3

Sample #	Orientation	Dip	Sample #	Orientation	Dip
4A	137	27	4B	110	12
	105	16		69	27
	334	1		294	17
	173	20		105	19
	255	45		155	7
	172	36		25	22
	75	31		274	7
	135	5		121	12
	203	4		228	7
	107	9		305	65
	135	4		137	29
	318	32		5	52
	236	7		336	18
	40	19		66	57
	129	5		109	7
	241	2		130	29
	228	9		163	33
	297	18		279	8
	339	5		109	1
	120	1		187	11
	55	16		252	7
	42	13		286	14
	31	22		163	14
	62	26		335	11
	305	30		160	9
	87	1		193	1
	344	27		308	16
	304	11		82	19
	265	3		78	12
	274	10		287	22
	333	2		319	8
	243	3		235	47
	281	1		291	1
	299	8		150	15
	101	2		308	19
	82	8		143	33
	218	11		295	2
	123	15		297	19
	147	34		134	26
	243	24		259	9
	220	12		281	23
	327	7		338	2
	131	1		97	2
	248	36		335	2
	158	23		115	10
	128	2		125	25
	334	10		113	4
	271	16		312	33
	337	4		123	10
	223	43		112	18

Sample #	Orientation	Dip	Sample #	Orientation	Dip
4C	219	5	4D	3	18
	351	23		348	22
	212	15		10	7
	215	11		15	74
	338	3		355	20
	29	6		12	0
	3	5		307	5
	205	16		108	3
	68	4		48	4
	266	61		12	36
	248	19		66	19
	333	3		39	19
	38	4		6	10
	144	17		11	7
	155	49		283	10
	112	7		20	4
	91	0		157	13
	290	45		23	17
	342	17		210	16
	204	10		144	7
	5	6		259	1
	190	2		331	13
	312	8		308	31
	172	10		346	30
	20	11		301	6
	191	8		342	4
	321	15		66	1
	28	7		160	1
	173	30		229	4
	343	6		137	17
	145	9		82	12
	194	15		296	20
	45	60		274	23
	328	42		282	11
	41	29		307	23
	289	16		330	42
	177	17		156	19
	165	20		88	2
	359	1		325	24
	145	8		251	15
	312	7		304	22
	300	4		159	6
	358	1		12	17
	178	18		251	9
	243	0		136	19
	296	16		268	23
	7	10		141	7
	320	16		116	2
	316	6		313	7
	308	25		322	13

Sample #	Orientation	Dip	Sample #	Orientation	Dip
4E	317	14	4F	202	60
	352	7		337	32
	330	14		302	15
	205	12		304	15
	315	17		123	60
	230	8		302	8
	145	37		125	20
	0	33		306	7
	28	39		141	50
	41	75		178	1
	322	28		174	20
	330	50		356	7
	163	44		158	22
	318	13		298	5
	335	14		358	64
	337	18		134	23
	316	25		124	24
	310	20		298	22
	174	9		269	10
	355	47		283	12
	58	17		270	13
	237	46		273	4
	241	20		88	2
	326	65		95	7
	126	1		170	3
	300	52		94	0
	265	12		282	12
	350	6		136	14
	349	26		344	48
	331	25		275	12
	327	59		126	18
	324	23		276	25
	306	26		180	58
	300	28		302	20
	41	4		303	8
	249	55		277	11
	225	42		270	77
	304	10		350	53
	113	13		302	41
	67	4		310	54
	307	35		347	50
	329	24		303	27
	331	19		314	23
	297	25		312	39
	308	22		132	50
	208	21		310	44
	260	13		331	32
	28	10		314	7
	301	42		152	65
	46	37		114	56

Sample #	Orientation	Dip	Sample #	Orientation	Dip
5A	178	8	5B	339	19
	246	7		332	12
	140	14		185	72
	110	18		152	31
	49	25		119	32
	116	37		151	61
	194	37		145	24
	315	3		282	4
	240	22		4	32
	314	16		141	12
	184	8		53	14
	133	5		205	25
	318	47		305	9
	309	26		145	7
	153	13		31	4
	114	6		324	7
	90	8		206	16
	278	17		144	4
	168	8		65	71
	140	10		117	36
	242	23		55	43
	256	18		150	13
	320	11		159	48
	229	28		166	58
	227	5		122	7
	323	42		146	19
	336	50		142	31
	214	12		196	39
	19	8		10	12
	316	14		158	25
	270	5		25	22
	215	10		354	13
	56	3		321	1
	129	17		126	62
	268	37		173	44
	207	18		309	19
	97	25		156	9
	137	12		168	9
	198	8		20	6
	154	1		263	5
	220	8		184	29
	130	53		159	45
	208	6		335	35
	70	7		32	15
	326	14		180	15
	238	11		182	22
	232	4		198	24
	225	6		159	32
	23	14		165	16
	311	13		144	19

Sample #	Orientation	Dip	Sample #	Orientation	Dip
5C	141	25	5D	184	0
	60	45		174	8
	296	3		240	25
	140	5		156	34
	5	35		294	4
	218	17		323	17
	299	13		235	18
	328	32		337	55
	153	33		140	5
	83	31		212	27
	180	19		149	14
	16	25		329	25
	5	49		28	14
	343	8		165	22
	203	10		77	50
	103	11		2	19
	197	32		6	12
	172	34		114	22
	237	5		301	19
	170	26		81	53
	139	7		300	10
	292	19		165	32
	290	32		146	16
	172	4		276	25
	62	12		175	14
	349	24		142	14
	35	14		8	3
	270	25		207	20
	37	16		3	22
	127	2		222	25
	92	28		158	6
	293	3		47	24
	80	36		280	20
	299	5		214	42
	295	40		71	32
	209	42		184	32
	38	13		323	34
	177	22		240	16
	124	25		326	51
	315	23		158	22
	131	5		164	20
	67	7		149	30
	316	17		274	13
	81	2		168	19
	304	52		139	1
	240	44		168	18
	152	14		3	5
	328	37		183	19
	137	43		161	23
	344	11		149	19

Sample #	Orientation	Dip	Sample #	Orientation	Dip
5E	86	17	5F	302	31
	65	24		131	27
	144	21		223	19
	135	14		49	16
	207	1		187	3
	50	47		122	19
	11	1		125	16
	138	15		128	10
	207	70		230	10
	110	13		126	17
	134	16		230	22
	321	18		321	17
	284	17		215	13
	131	31		208	20
	305	11		165	20
	115	9		219	19
	125	18		138	18
	325	16		141	40
	141	22		92	9
	126	26		50	4
	89	26		99	15
	144	7		64	10
	144	18		27	24
	134	19		208	34
	47	12		90	10
	151	23		95	33
	125	37		135	37
	33	38		251	39
	320	28		278	9
	164	29		271	10
	352	25		266	5
	148	12		193	22
	76	35		241	21
	129	42		18	22
	145	21		184	12
	320	39		43	3
	167	10		111	48
	155	21		153	16
	228	30		185	14
	131	13		170	30
	144	64		196	27
	122	34		202	3
	224	11		170	25
	322	39		176	36
	299	39		283	47
	116	29		198	7
	118	27		38	17
	297	9		267	34
	134	21		244	33
	152	15		228	29

Sample #	Orientation	Dip	Sample #	Orientation	Dip
6A	78	16	6F	258	20
	76	28		171	31
	101	36		250	24
	354	45		282	14
	65	24		287	6
	310	22		24	9
	325	18		306	8
	193	13		217	30
	76	16		331	0
	329	29		323	9
	75	43		13	9
	352	31		255	64
	345	37		154	26
	182	3		135	7
	315	15		99	5
	4	37		185	0
	168	12		269	17
	106	34		75	10
	34	34		177	53
	313	36		33	6
	298	30		18	27
	100	28		52	17
	322	24		4	23
	96	3		261	63
	338	44		263	24
	5	36		166	45
	254	41		280	9
	3	31		292	9
	57	14		298	28
	65	14		159	22
	349	22		303	18
	97	16		37	26
	340	15		268	2
	70	48		192	35
	17	27		304	22
	129	5		145	0
	127	7		8	38
	349	26		240	23
	30	60		332	35
	40	24		67	15
	22	22		289	45
	337	35		282	12
	297	21		283	44
	287	30		343	23
	183	10		300	25
	164	9		105	41
	188	13		221	5
	0	24		106	8
	288	8		204	22
	168	5		76	20

Appendix H

Microfabric Data

Microfabric Data

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
1A	108	150	19	45	21	35
	75	169	5	14	21	19
	44	104	13	22	33	5
	90	128	44	9	8	11
	173	159	12	60	6	20
	132	81	15	8	7	28
	53	96	20	12	7	19
	20	79	35	25	15	8
	15	6	10	5	1	31
	61	23	19	13	27	37
	114	163	6	31	53	30
	42	155	6	22	19	17
	149	141	7	10	9	54
	125	2	21	13	35	17
	152	9	39	34	52	37
	43	55	38	7	23	24
	43	104	43	3	4	18
	15	92	14	37	6	4
	40	155	36	30	59	27
	67	159	11	13	17	8
	6	132	3	5	10	
	27	173	1	40		
	50	164	15	1		
	84	145	6	23		
	147	120	38	4		
	152	148	12	4		
	92	101	35	39		
	74	92	5	41		
	16	116	73	13		
	131	87	6			
	122	126				
	146	7				
	152	136				
	132	132				
	5	143				
	131	107				
	31	65				
	74	80				
	144	104				
	145	63				
	99	21				
	146	83				
	153	51				
	125	142				
	128	46				
	83	42				
	75	163				
	163	6				
	117	137				
	108	125				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
1B	118	141	73	4	29	8
	59	130	54	45	17	12
	124	118	32	52	11	16
	12	120	30	3	6	20
	174	154	56	10	25	30
	52	140	32	23	30	37
	139	128	37	65	22	46
	24	146	10	50	54	15
	160	123	2	12	10	35
	61	37	19	5	11	60
	165	157	8	8	15	8
	55	147	12	42	44	5
	139	168	29	54	12	36
	95	70	23	17	52	53
	114	167	1	27	7	41
	131	172	8	30	46	22
	172	0	14	19	26	28
	177	126	34	13	14	32
	66	114	62	26	11	
	7	100	21	28		
	128	140	4	16		
	83	140	7	10		
	120	151	17	14		
	123	146	3	3		
	104	55	1	15		
	144	87	15	7		
	122	147	15	33		
	86	160	43	21		
	43	71	34	42		
	137	172	14	29		
	67	139	2	13		
	158	27	17			
	125	145				
	84	23				
	134	7				
	168	169				
	34	131				
	78	21				
	118	159				
	145	5				
	170	162				
	84	139				
	155	32				
	167	12				
	177	136				
	112	79				
	154	93				
	168	150				
	50	8				
	37	153				

			Dips			
Sample #	**Orientations**		**Up-ice**		**Down-ice**	
1C	118	55	34	40	22	5
	142	39	54	22	40	4
	115	63	44	48	39	14
	149	162	2	32	18	18
	92	138	3	68	49	55
	85	121	72	74	13	8
	58	49	8	22	32	72
	100	104	13	61	58	18
	55	89	8	21	37	37
	34	164	31	13	20	67
	75	5	27	16	18	2
	100	95	27	15	8	21
	80	10	46	13	9	76
	103	23	46	1	2	58
	112	52	16	3	17	70
	114	150	29	19	46	18
	97	45	42	52	17	13
	100	5	47	39	10	4
	91	67	42	23		
	25	30	42	7		
	6	102	7	22		
	22	173	26	23		
	79	175	4	27		
	113	159	23	14		
	117	73	46	41		
	82	89	17	23		
	32	63	6	43		
	30	104	12	31		
	63	83	16	22		
	55	38	18	3		
	51	94	42	21		
	44	88	2	12		
	60	63				
	60	65				
	52	24				
	73	82				
	135	85				
	111	107				
	137	87				
	143	108				
	23	63				
	71	67				
	73	38				
	102	79				
	93	151				
	61	98				
	46	74				
	66	78				
	33	2				
	81	2				

			Dips			
Sample #	Orientations		Up-ice		Down-ice	
1D	157	25	19	30	24	32
	22	130	4	18	7	10
	178	20	3	53	18	12
	28	45	9	1	17	28
	151	91	8	14	15	26
	157	109	13	11	11	3
	69	117	3	8	38	5
	24	166	25	64	50	13
	34	70	24	28	69	27
	6	143	27	7	1	8
	8	2	1	12	1	8
	8	166	24	39	37	2
	55	123	5	48	2	25
	55	2	36	16	3	21
	124	43	12	5	40	5
	131	125	19	4	13	20
	9	131	8	23	1	7
	63	157	17	13	8	
	91	40	13	50		
	105	23	16	52		
	120	39	1	14		
	18	13	37	8		
	8	26	41	13		
	81	17	11	14		
	70	131	1	28		
	144	34	17	30		
	176	66	4	41		
	50	167	33	69		
	179	22	11	63		
	3	6	8	44		
	173	12	7	24		
	80	12	31	7		
	135	179	33	19		
	102	179	14			
	5	11				
	119	7				
	44	28				
	83	162				
	105	168				
	8	26				
	167	156				
	134	2				
	32	151				
	36	5				
	90	38				
	121	49				
	1	40				
	34	102				
	27	177				
	47	37				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
1E	51	162	15	31	33	35
	1	164	5	18	40	45
	21	20	34	42	74	64
	85	108	67	8	65	71
	51	93	26	3	77	54
	5	128	45	17	50	32
	148	88	1	23	10	23
	144	47	10	37	62	40
	127	108	27	55	61	40
	133	75	34	63	5	42
	13	38	35	77	3	62
	67	10	56	4	6	24
	39	95	75	3	14	5
	85	79	61	22	31	3
	7	137	18	31	2	3
	135	176	3	24	22	68
	176	137	27	77	54	22
	155	96	10	35	30	44
	57	57	44	79	4	53
	51	124	8	72	2	54
	73	12	77	12		
	127	28	37	3		
	172	43	45	9		
	26	95	67	1		
	59	65	40	9		
	60	165	40	31		
	37	87	74	5		
	82	69	75	42		
	90	93	67	11		
	119	69	35	20		
	35	161				
	42	51				
	152	150				
	79	62				
	119	120				
	139	140				
	102	168				
	11	14				
	48	176				
	20	49				
	111	63				
	60	132				
	42	94				
	27	28				
	72	56				
	139	3				
	40	143				
	179	172				
	179	104				
	114	84				

			Dips			
Sample #	**Orientations**		**Up-ice**		**Down-ice**	
1F	29	66	16	8	61	37
	143	24	1	41	9	16
	120	165	58	3	16	54
	87	140	4	30	44	67
	85	66	29	56	35	3
	107	143	31	2	35	2
	46	135	14	15	28	1
	48	169	10	30	15	13
	37	146	2	18	47	9
	87	99	2	58	15	3
	78	100	13	14	5	47
	22	175	2	30	14	18
	76	50	60	31	25	5
	94	178	1	1	4	8
	73	30	33	51	15	21
	61	30	62	28	60	76
	117	2	33	49	9	23
	179	43	16	70		
	120	20	34	12		
	7	36	46	29		
	49	123	32	57		
	154	158	21	28		
	37	64	14	37		
	50	91	34	61		
	54	42	38	55		
	91	23	52	27		
	54	40	5	35		
	43	84	21	36		
	44	104	19	21		
	41	122	9	32		
	99	132	7	31		
	104	51	40	20		
	78	13	34	51		
	12	132				
	45	93				
	63	115				
	108	57				
	46	177				
	28	71				
	168	160				
	174	27				
	42	97				
	46	147				
	9	139				
	3	132				
	83	119				
	87	62				
	22	51				
	110	91				
	54	85				

			Dips			
Sample #	Orientations		Up-ice		Down-ice	
3A	132	124	26	14	10	3
	143	161	6	50	30	2
	158	132	33	32	10	31
	121	78	28	33	8	58
	121	48	22	12	26	7
	151	102	1	30	15	28
	136	131	39	26	4	16
	16	134	8	27	13	67
	113	162	8	24	5	24
	137	137	35	24	42	17
	122	140	20	19	17	51
	161	118	15	4	24	39
	179	168	42	3	12	1
	60	172	55	7	19	30
	122	132	23	3	21	52
	158	171	58	2	31	32
	162	137	22	42	73	2
	139	66	37	23	30	3
	29	73	44	40		
	121	44	28	24		
	109	32	18	42		
	141	13	76	30		
	148	87	68	63		
	162	149	55	40		
	157	158	58	1		
	25	37	3	8		
	163	87	36	20		
	145	178	29	21		
	160	159	44	43		
	17	120	1	4		
	98	138	26	58		
	73	176	16	40		
	7	157				
	19	16				
	77	28				
	15	15				
	156	140				
	120	77				
	78	33				
	87	176				
	70	126				
	39	157				
	102	100				
	166	162				
	3	161				
	144	141				
	168	153				
	158	129				
	146	149				
	128	157				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
3B	159	41	21	25	14	50
	124	104	54	8	69	46
	108	108	24	79	68	26
	106	116	14	44	3	25
	70	149	5	10	1	5
	71	143	36	78	70	13
	99	29	51	43	10	44
	22	160	64	7	42	9
	179	118	8	34	4	25
	15	117	21	50	29	8
	2	135	8	37	35	30
	9	152	19	1	68	27
	144	59	21	39	53	49
	15	70	41	56	44	74
	155	87	50	57	5	10
	152	113	59	48	34	18
	45	121	62	47	23	29
	154	177	26	23	47	13
	172	37	44	45	29	7
	155	160	18	60	32	42
	151	41	27	32	31	13
	58	55	6	29	78	15
	177	55	15	40	22	19
	11	78	15	26		
	142	48	8	17		
	65	4	49	8		
	151	7	1	25		
	152	176				
	15	24				
	158	114				
	148	8				
	6	38				
	26	56				
	32	64				
	97	16				
	142	140				
	32	89				
	94	82				
	149	61				
	62	39				
	11	56				
	73	28				
	88	137				
	29	123				
	72	74				
	36	147				
	58	88				
	4	163				
	41	56				
	167	109				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
3C	115	172	44	3	66	2
	147	35	38	38	9	8
	117	142	47	27	52	16
	27	176	33	48	25	39
	18	20	26	38	67	63
	47	55	62	41	15	72
	41	43	28	44	33	12
	55	169	21	66	16	17
	8	93	35	13	37	9
	27	105	46	7	42	9
	27	128	53	1	75	33
	56	14	36	23	14	18
	48	38	25	8	39	21
	65	12	36	14	24	38
	67	15	66	53	47	58
	64	125	55	12	8	60
	157	150	10	21	71	34
	169	26	58	55	15	
	29	54	49	22		
	124	44	71	26		
	95	11	69	44		
	153	42	51	13		
	45	13	58	17		
	51	20	66	14		
	70	157	1	49		
	49	14	10	23		
	14	102	34	16		
	18	119	10	27		
	137	43	49	20		
	22	113	39	65		
	39	38	63	32		
	68	9	13	46		
	86	15	1			
	134	68				
	179	23				
	28	46				
	132	8				
	139	29				
	108	154				
	45	60				
	3	167				
	167	155				
	2	83				
	59	140				
	71	101				
	13	161				
	52	177				
	29	28				
	31	6				
	41	174				

			Dips			
Sample #	**Orientations**		**Up-ice**		**Down-ice**	
3D	159	12	35	37	2	9
	152	1	17	17	8	19
	149	170	20	28	8	5
	114	27	38	52	3	23
	15	43	37	41	45	19
	44	10	15	17	5	68
	37	52	39	50	12	5
	147	110	48	49	28	38
	0	9	32	13	22	14
	155	39	29	27	4	63
	162	0	9	47	17	5
	16	70	7	29	55	38
	58	100	23	26	13	7
	105	5	1	2	3	12
	99	25	6	8	9	1
	65	175	20	29	12	4
	34	177	43	22	31	21
	33	170	22	5	63	49
	13	116	10	2	40	8
	119	164	4	7	25	18
	94	24	13	33	39	7
	56	25	6	28	5	8
	75	16	14	27	3	
	42	78	64	6		
	0	79	15	6		
	170	69	43	24		
	149	87	19	16		
	114	38	29			
	101	63				
	61	68				
	50	76				
	22	44				
	6	85				
	1	171				
	11	169				
	138	145				
	178	35				
	177	41				
	172	133				
	10	137				
	1	156				
	11	32				
	3	90				
	3	148				
	178	165				
	32	111				
	36	43				
	20	157				
	27	133				
	34	175				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
3E	148	16	6	42	2	23
	165	1	17	20	58	23
	153	163	35	31	57	75
	15	169	52	18	73	35
	138	158	169	3	45	2
	6	28	45	32	19	52
	17	80	66	70	8	34
	165	45	49	48	5	40
	108	24	5	7	16	21
	133	165	3	52	16	7
	46	108	29	27	5	68
	94	163	41	53	41	76
	3	114	39	47	64	39
	5	170	40	8	5	3
	40	162	40	35	57	1
	65	165	17	21	7	25
	3	27	52	5	22	8
	31	174	44	8	14	7
	7	138	3	24	31	10
	149	113	49	56	22	18
	12	115	12	53		
	150	115	37	5		
	36	2	20	32		
	41	72	10	6		
	21	36	39	1		
	12	74	49	5		
	82	143	40	28		
	8	20	24	30		
	133	42	21	23		
	153	163	24	5		
	162	42				
	16	34				
	37	2				
	20	22				
	166	14				
	168	13				
	143	68				
	4	29				
	9	41				
	148	133				
	175	56				
	167	73				
	147	7				
	5	35				
	165	138				
	15	22				
	24	32				
	101	0				
	42	154				
	7	5				

Sample #	Orientations		Up-ice		Down-ice	
3F	144	91	32	15	15	13
	141	56	17	77	36	10
	177	140	13	7	36	48
	165	53	28	12	12	58
	131	79	28	12	18	46
	123	158	29	9	26	14
	61	81	21	43	11	34
	41	38	22	24	51	40
	99	45	43	43	22	17
	134	67	29	42	19	7
	83	90	3	57	20	5
	2	28	20	8	21	11
	86	149	39	11	4	23
	7	21	22	4	9	26
	143	56	20	12	29	41
	29	43	21	28	8	6
	86	112	65	44	21	3
	32	81	74	38	4	36
	59	89	22	41	27	43
	59	87	3	43	1	
	51	93	1	72		
	33	92	1	58		
	166	141	5	44		
	92	94	68	6		
	141	134	49	38		
	93	87	11	14		
	91	52	55	12		
	94	18	13	9		
	148	80	47	6		
	101	108	44	2		
	93	22	40			
	88	149				
	158	118				
	35	161				
	171	9				
	22	23				
	98	41				
	137	49				
	62	128				
	46	4				
	33	96				
	26	123				
	64	109				
	124	135				
	126	5				
	95	78				
	118	90				
	140	86				
	177	44				
	147	95				

			Dips			
Sample #	Orientations		Up-ice		Down-ice	
5A	156	130	32	38	72	7
	147	178	56	37	3	6
	38	155	53	20	19	26
	147	159	9	8	49	55
	126	139	7	25	69	31
	79	144	31	52	49	21
	44	16	37	7	4	3
	169	104	11	3	2	12
	128	171	34	2	1	5
	43	102	56	1	19	1
	42	43	59	42	1	11
	3	70	16	2	21	64
	15	148	74	8	31	48
	64	154	4	22	38	52
	55	3	17	1	1	19
	12	168	12	32	6	2
	77	111	12	25	19	3
	175	90	17	48	11	29
	116	136	44	34	31	23
	145	83	30	45		
	29	62	17	52		
	144	108	6	3		
	137	159	29	8		
	173	0	5	52		
	100	142	4	11		
	111	148	4	36		
	108	93	43	35		
	7	86	56	13		
	113	97	21	11		
	131	173	42	18		
	4	144	8	3		
	155	110				
	34	131				
	149	123				
	156	84				
	0	72				
	71	136				
	33	158				
	32	139				
	103	11				
	124	27				
	28	173				
	104	13				
	46	70				
	110	105				
	172	113				
	158	123				
	24	67				
	68	134				
	156	148				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
5B	129	92	9	43	4	7
	126	44	10	19	8	25
	134	165	25	1	13	42
	119	93	11	22	23	22
	110	155	24	55	28	24
	128	100	21	2	13	23
	2	84	33	14	43	2
	1	148	51	8	67	1
	157	79	9	5	41	69
	128	158	6	28	3	3
	149	129	19	31	15	36
	151	0	4	2	5	38
	123	86	55	19	18	60
	77	129	6	5	48	44
	112	42	52	25	51	16
	149	147	23	56	53	37
	179	162	41	8	40	37
	153	63	27	23	12	33
	145	27	11	13	19	14
	18	63	45	28		
	163	73	30	14		
	163	138	38	29		
	157	10	45	28		
	149	128	50	13		
	154	164	9	1		
	174	159	1	11		
	142	135	8	1		
	144	149	22	8		
	177	123	37	34		
	169	129	63	50		
	161	135	36	17		
	11	140				
	154	31				
	12	164				
	171	17				
	138	13				
	142	71				
	116	127				
	72	161				
	66	152				
	108	144				
	173	174				
	140	161				
	128	132				
	146	175				
	141	2				
	149	98				
	118	44				
	136	130				
	70	149				

			Dips			
Sample #	Orientations		Up-ice		Down-ice	
5C	179	30	45	28	43	68
	154	4	48	22	28	19
	3	46	36	8	14	43
	176	40	1	32	55	12
	27	132	12	37	74	41
	37	137	2	27	65	30
	28	168	23	41	39	9
	65	157	48	1	7	1
	53	136	58	10	63	10
	92	33	63	47	29	42
	105	16	25	56	2	30
	80	5	7	43	4	9
	18	177	25	33	6	10
	143	159	25	10	20	33
	34	157	8	41	25	14
	74	108	39	15	16	28
	80	64	36	50	73	61
	122	173	17	26	63	19
	11	42	13	53	44	24
	66	8	33	35	56	
	149	35	21	11		
	166	22	9	28		
	3	3	5	41		
	18	52	44	36		
	28	68	32	15		
	16	57	46	14		
	59	39	7	43		
	38	51	24	4		
	165	41	48	43		
	16	7	39	26		
	35	21	57			
	69	172				
	90	6				
	120	27				
	22	18				
	4	26				
	49	82				
	38	108				
	9	77				
	20	65				
	20	60				
	177	29				
	2	48				
	53	164				
	20	47				
	10	166				
	8	122				
	167	70				
	119	104				
	176	32				

Sample #	Orientations		Up-ice		Down-ice	
5D	37	43	12	17	15	8
	21	50	17	14	30	31
	16	146	8	29	15	73
	152	11	16	8	19	1
	113	46	32	23	4	38
	28	56	55	10	35	22
	7	152	5	21	1	13
	38	150	18	8	21	10
	19	176	24	1	6	24
	168	80	17	32	20	21
	148	60	15	20	8	15
	137	29	32	12	26	26
	97	160	18	7	7	36
	42	137	7	32	2	12
	37	15	31	21	42	10
	28	178	17	62	12	8
	166	13	3	36	2	68
	145	4	28	52	26	64
	138	52	26	21	3	
	166	2	37	6		
	1	43	10	30		
	10	23	37	11		
	27	12	8	11		
	53	23	45	2		
	47	55	10	23		
	179	37	4	26		
	14	20	3	2		
	27	32	56	37		
	50	0	20	13		
	12	43	13	48		
	27	56	12	34		
	140	43	2			
	98	26				
	68	163				
	147	17				
	12	167				
	18	21				
	130	24				
	37	47				
	149	156				
	144	167				
	22	6				
	8	33				
	59	63				
	37	24				
	177	169				
	53	156				
	32	10				
	15	18				
	35	28				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
5E	130	62	8	55	6	18
	171	170	47	50	6	5
	50	152	5	53	1	12
	13	48	17	14	8	12
	29	60	4	15	15	2
	41	68	37	10	3	7
	39	147	39	29	25	8
	123	19	6	7	13	8
	78	53	37	31	10	29
	34	89	39	3	13	5
	55	109	12	7	15	15
	52	26	52	29	50	14
	104	80	41	13	36	4
	110	85	3	12	12	18
	77	123	43	33	43	37
	48	128	6	43	13	35
	7	16	14	51	4	
	57	78	41	23		
	87	105	48	9		
	86	13	4	1		
	28	108	14	17		
	58	98	13	42		
	69	78	8	5		
	29	89	30	43		
	82	83	12	23		
	16	112	25	42		
	174	107	6	35		
	8	124	33	63		
	50	99	19	37		
	56	24	44	23		
	114	46	56	39		
	122	96	28	16		
	124	84	72	25		
	110	16	28			
	126	2				
	115	134				
	92	77				
	101	105				
	30	89				
	52	89				
	62	87				
	81	79				
	149	168				
	134	153				
	43	131				
	87	95				
	108	112				
	99	78				
	78	87				
	57	84				

Sample #	Orientations		Dips			
			Up-ice		Down-ice	
5F	77	77	16	46	16	12
	91	89	56	54	30	9
	88	67	14	6	43	17
	109	78	26	2	12	15
	95	87	36	11	7	32
	83	105	19	4	28	38
	43	45	9	18	34	14
	129	173	7	64	13	14
	111	127	36	7	11	63
	93	14	2	7	57	28
	79	12	32	24	47	43
	100	34	43	11	62	56
	112	12	34	15	1	57
	94	32	45	50	5	2
	29	92	19	5	5	17
	84	105	9	5	75	8
	39	80	38	4	10	14
	32	46	18	54		
	11	24	8	42		
	71	85	65	23		
	63	85	41	38		
	94	151	18	7		
	71	2	14	36		
	40	27	3	55		
	97	55	24	55		
	163	108	16	20		
	87	63	42	6		
	58	98	17	13		
	134	168	9	21		
	151	11	38	13		
	75	56	71	23'		
	93	164	27	7		
	138	175	34	16		
	67	87				
	86	30				
	166	53				
	29	89				
	172	156				
	129	154				
	178	156				
	35	76				
	56	68				
	85	82				
	69	78				
	116	70				
	160	80				
	94	98				
	91	128				
	54	103				
	61	116				